AN ANALYSIS OF THE ORTHOGONAL METAL CUTTING PROCESS

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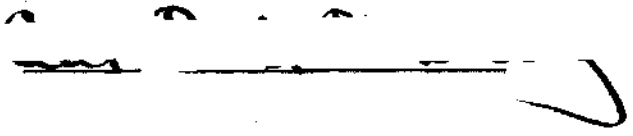

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SUMMARY

Previous analyses concerning the mechanics of the orthogonal metal cutting process have produced relationships between the various angle parameters. These relationships cannot be used to predict the geometry of cutting or tool forces, and hence are limited in applicability and usefulness.

The purpose of the investigation is two-fold; first to determine experimentally the effect of changes in the rake angle and cutting speed on the type of chip produced during orthogonal machining of aluminum and then to develop a generalized model of the orthogonal metal cutting process which will predict the chip geometry and the effects of changes in rake angle and cutting speed on tool forces from a knowledge of the effects of strain, strain rate, and temperature on the mechanical properties of the work material.

It is believed that the present work represents considerable progress in the understanding of the mechanics of the machining process. The analysis shows excellent qualitative agreement between the predicted and experimentally measured cutting forces, friction angle, and chip thickness.

CHAPTER I

PROBLEM DEFINITION

Because of the complex nature of the metal cutting process no comprehensive theory has been proposed which will accurately describe the process without use of artificial parameters such as the shear angle, the friction angle, or a machinability constant. The problem is compounded by the fact that changes in cutting speed as well as changes in rake angle alter the chip geometry and tool forces during cutting.

The purpose of this research is to develop a comprehensive model of the metal cutting process which will qualitatively predict the effects of changes in rake angle and cutting speed on the tool forces and geometry of the cutting process.

CHAPTER II

REVIEW OF LITERATURE

Problem History

The metal cutting process is one of the oldest methods of reducing a metal workpiece to a given shape and is directly or indirectly involved in the manufacture of most of the items used today. Much work of an empirical nature has been carried out in the past concerning the development of new cutting techniques and methods to obtain reductions in machining costs and improvements in dimensional control. A much smaller amount of work has been carried out concerning attempts to understand the fundamental principals of the machining process. In recent years the amount of basic research has increased since it has been recognized that fundamental knowledge of the machining process can help in the solution of many practical production problems.

The machining process involves the systematic removal of layers of metal in the form of chips from a workpiece by the action of a wedge shaped cutting tool. Figure 1 illustrates the general case of cutting known as oblique cutting in which the cutting edge of the tool is straight and parallel with the original plane surface of the workpiece. The special case where the cutting edge of the tool is perpendicular to the direction of relative work tool motion is known as orthogonal cutting and is illustrated in Figure 2.

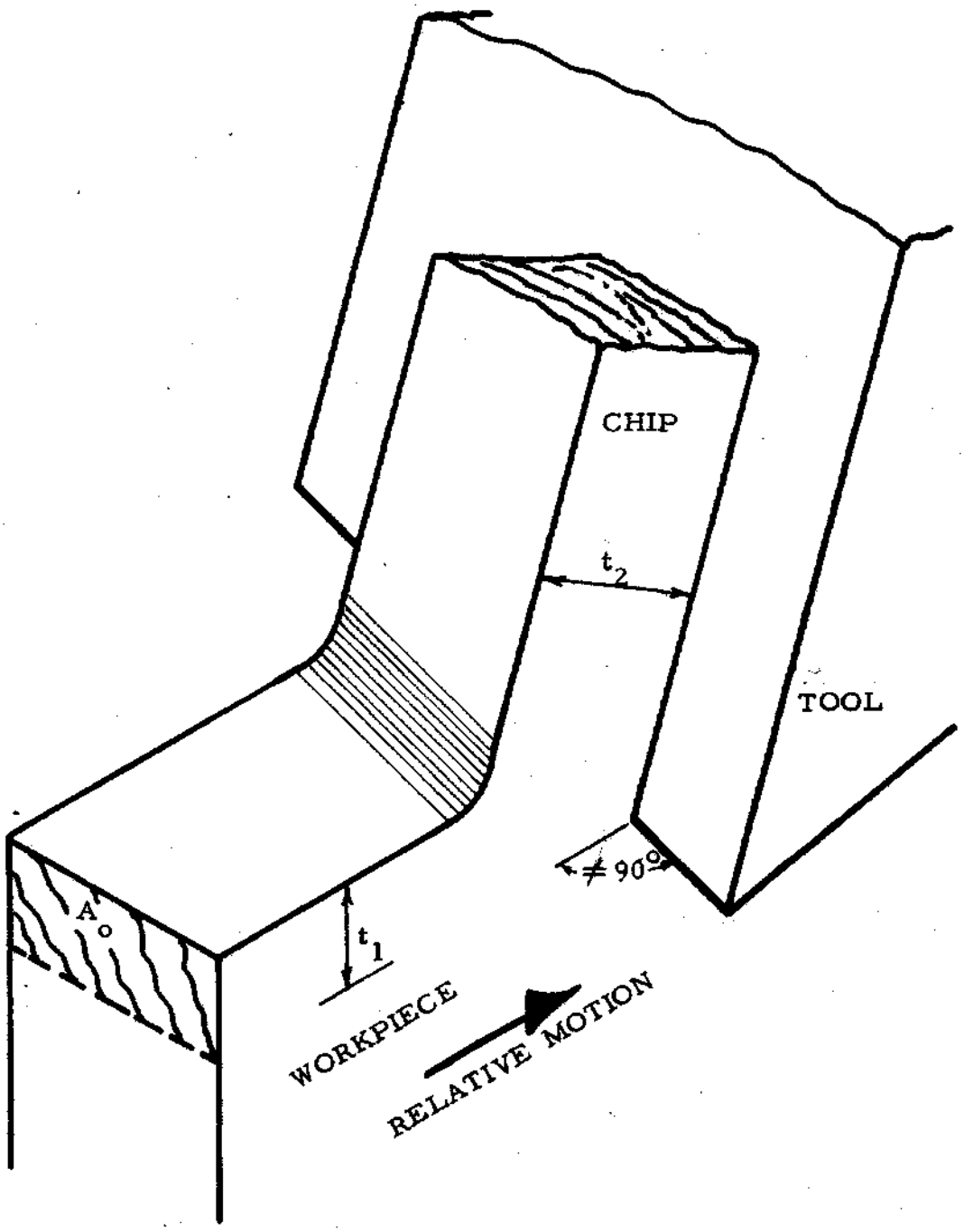


Figure 1: Oblique Cutting

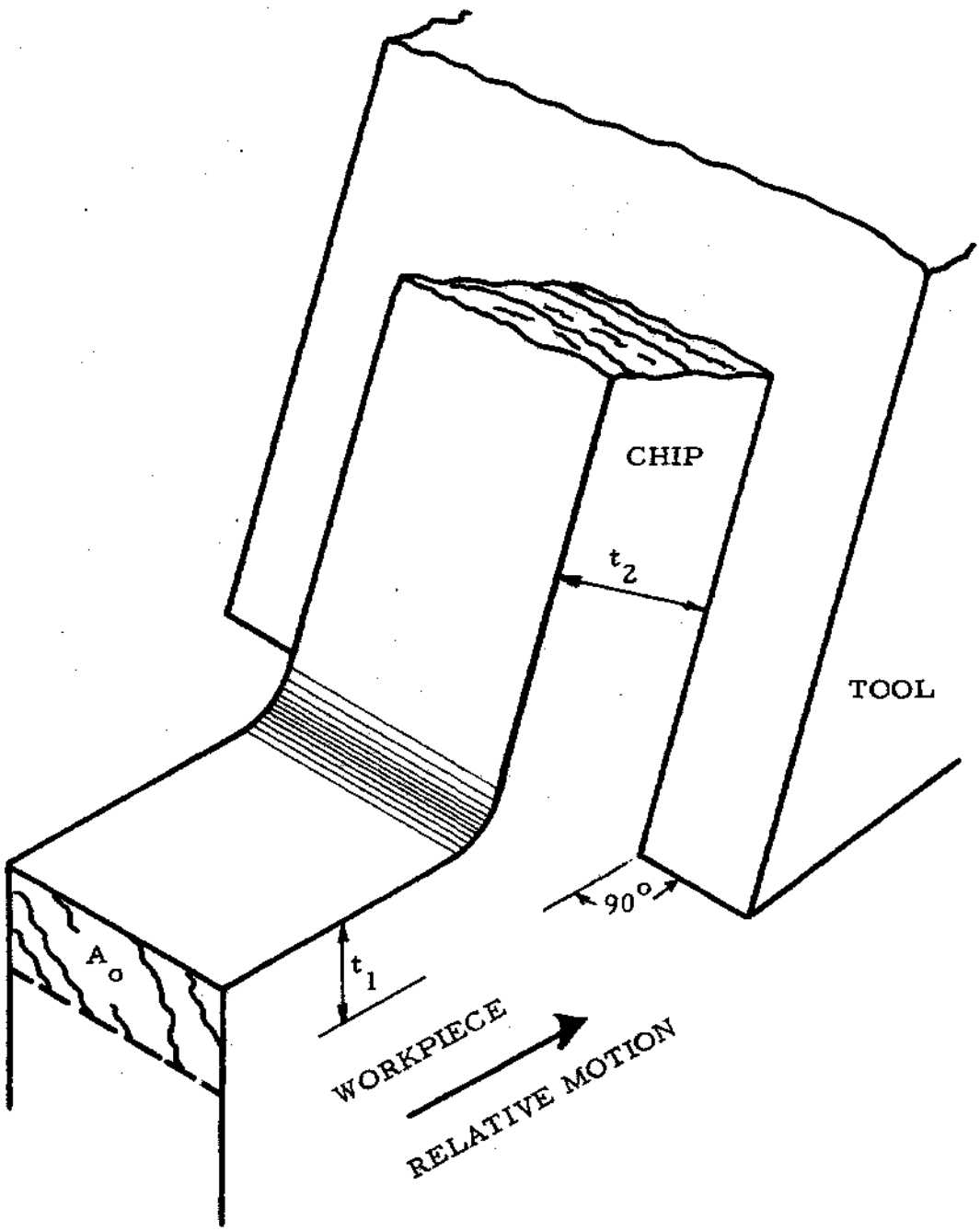


Figure 2: Orthogonal Cutting

Chip Formation

Since orthogonal cutting represents a two-dimensional or plane strain process rather than a three-dimensional process it lends itself well to analytical investigations where it is desirable to eliminate as many of the independent variables as possible.

In practical machining it is possible to produce three types of chip, namely:

(1) a continuous chip

(2) a continuous chip with a built-up edge on the tool face

(3) a discontinuous chip.

The type of chip produced in a particular machining operation is a function of the work and tool materials, the geometry and speed of the cutting process, and whether or not a lubricant is present.

When machining ductile materials such as mild steel, brass, or copper, continuous chips with the absence of a built-up edge on the tool face can be produced under certain conditions. Cutting under these conditions is a steady state process, and for this reason most of the work conducted in metal cutting research has dealt with continuous chip formation.

The formation of the chip takes place by shear in a zone extending from the tool cutting edge to the junction between the surfaces of the chip and the workpiece. This is known as the primary deformation zone, and is shown in Figure 3. The chip, which is substantially workhardened flows up the tool rake face under the action of large normal and frictional stresses. In unlubricated cutting the normal stress is such that

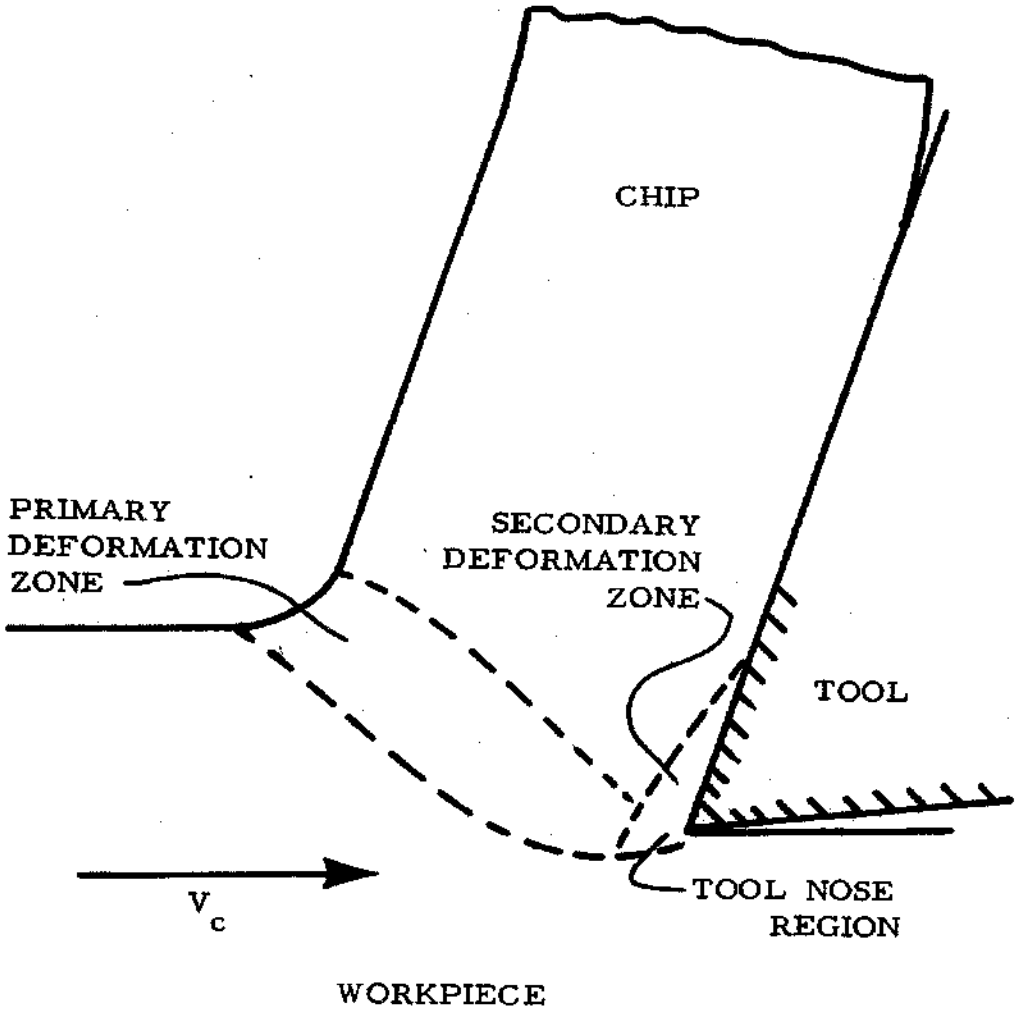


Figure 3: Metal Cutting Deformation Zones

the real and apparent areas of contact are equal over a portion of the chip-tool contact length. In this portion there is no relative motion at the chip-tool interface and deformation takes place in the lower layers of the chip (Secondary Deformation). This is also shown in Figure 3. Over the remaining portion of the chip-tool contact length the real area of contact is less than the apparent and relative motion at the interface can take place.

In the slow speed machining of certain ductile materials, it has been observed that a built-up edge forms on the took rake face. Under these conditions a portion of the chip material becomes anchored to the tool face and shearing takes place in a zone within the chip itself. During machining this built-up edge often grows until it becomes unstable and breaks away from the tool face. As the built-up edge disintegrates some fragments are carried past the tool by the new workpiece surface and some past the rake face by the underside of the chip causing damage in these regions.

Built-up edge formation in machining is usually an undesirable characteristic. It is one of the principal factors affecting surface finish and has a considerable influence on power consumption. The built-up edge is on occasion beneficial in that it reduces cutting tool wear when machining very abrasive materials by protection of the tool rake face. The built-up edge can be eliminated in a number of ways. It has generally been accepted that an increase in the workhardened state of the work material, the application of a lubricant, and an increase in rake angle all lead to a decrease in the speed below which a built-up edge will appear.

In machining brittle materials or ductile materials at very low speeds and high rates of feed, discontinuous chips are produced. In this case fracture occurs in the primary deformation zone and the chip becomes segmented.

Tool Forces and Their Measurement

In orthogonal cutting, the resultant force (R) applied to the chip by the tool lies in a plane normal to the cutting edge (Figure 4). This force is usually determined from the measurement of two orthogonal components; one in the direction of cutting (known as the cutting force, F_c); the other normal to the direction of cutting (known as the thrust force, F_t). The two components, F_c and F_t, are measured with a dynamometer.

Specific Cutting Pressure

The work done during cutting (W_{tl}) is the product of the cutting speed (V_c) and the cutting force (F_c), and is given by the expression:

$$W_{tl} = F_c V_c \quad . \tag{1}$$

A parameter which should give an indication of the efficiency of the metal cutting process, independent of cutting speed, is the work done per unit volume of metal removed (commonly known as the specific cutting pressure). This is given by the expression:

$$P_s = \frac{W_{tl}}{A_o V_c} \quad . \tag{2}$$

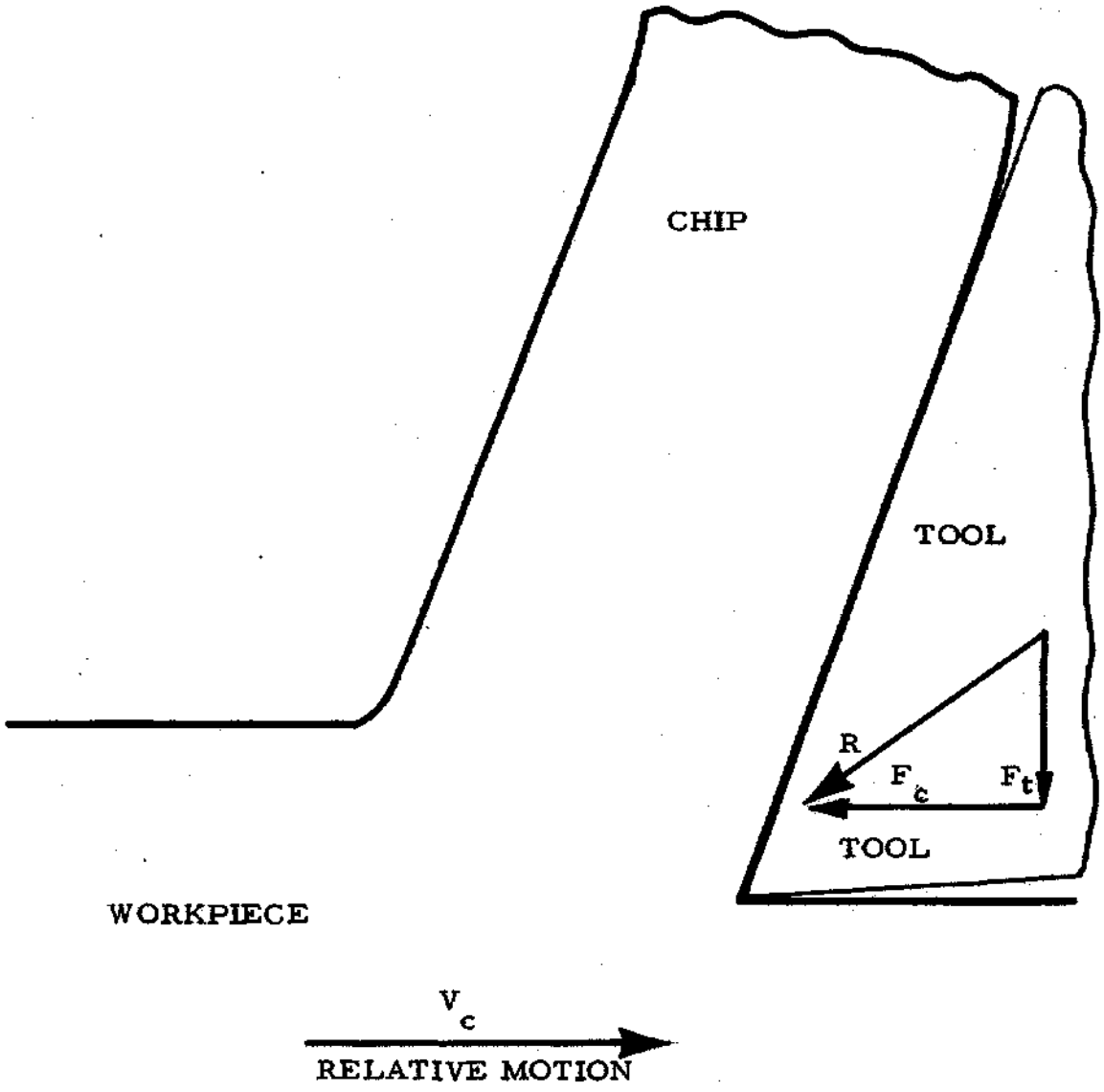


Figure 4. Characteristic Forces of Metal Cutting

Combining Equations (1) and (2) gives:

$$P_s = \frac{F_c}{w\ t_1} \text{ psi} \quad . \tag{3}$$

The specific cutting pressure can vary considerably for a given material and is affected by changes in cutting speed, tool rake angle, and undeformed chip thickness, at small values of t_1.

Mean Shear Strength of the Work Material

Figures 5 and 6 show the idealized model of the orthogonal metal cutting process where a continuous chip is produced with the absence of a built-up edge on the tool face. In this model the shear zone or primary deformation zone is represented by a plane, known as the shear plane. The angle of inclination of the shear plane, (ϕ), may be obtained from the expression:

$$\tan \phi = \frac{r_c \sin \alpha}{1 - r_c \cos \alpha} \quad , \tag{4}$$

where r_c is the cutting ratio and is given by:

$$r_c = \frac{t_1}{t_2} \quad . \tag{5}$$

In the experimental work, the tool rake angle (α) and the undeformed chip thickness (t_1) are known. The chip thickness (t_2) can be obtained by measurement with a ball ended micrometer or from the weight of a known length of chip.

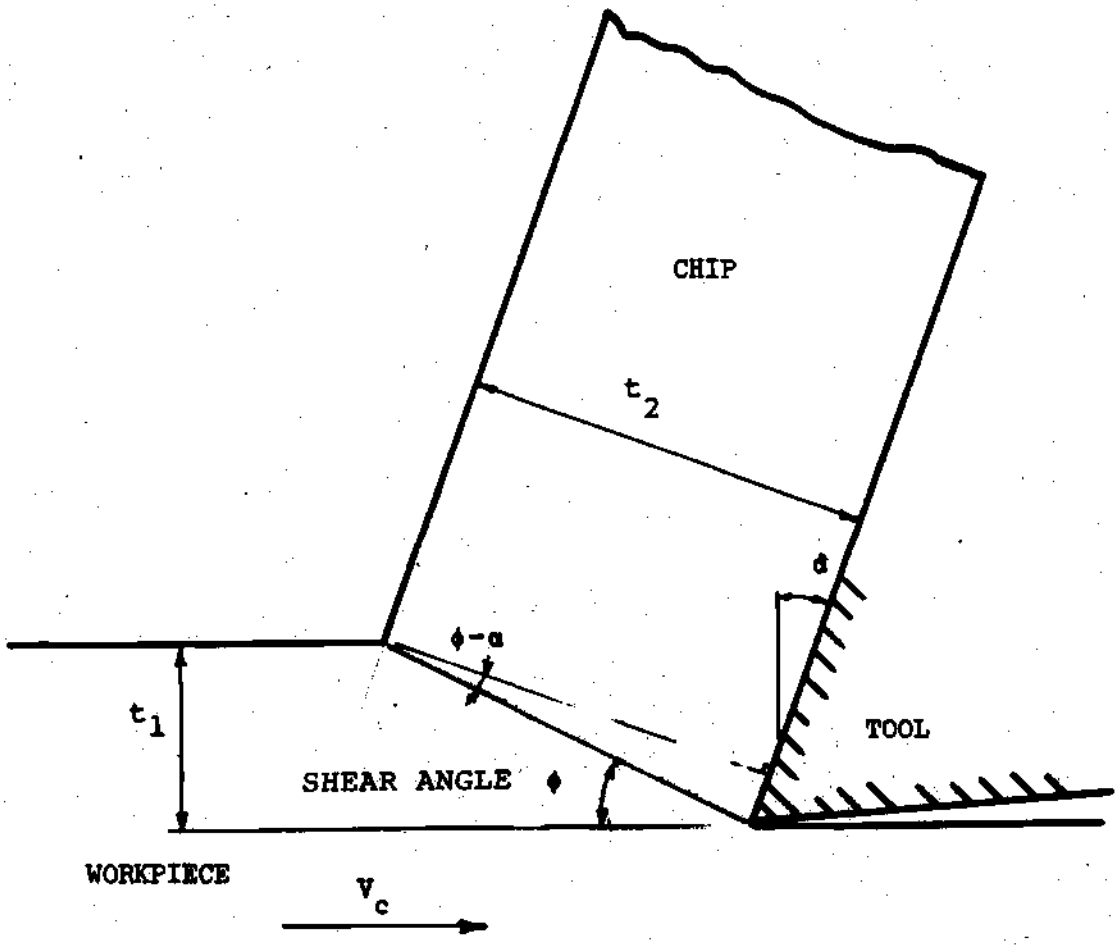


Figure 5: Model of Orthogonal Metal Cutting Process

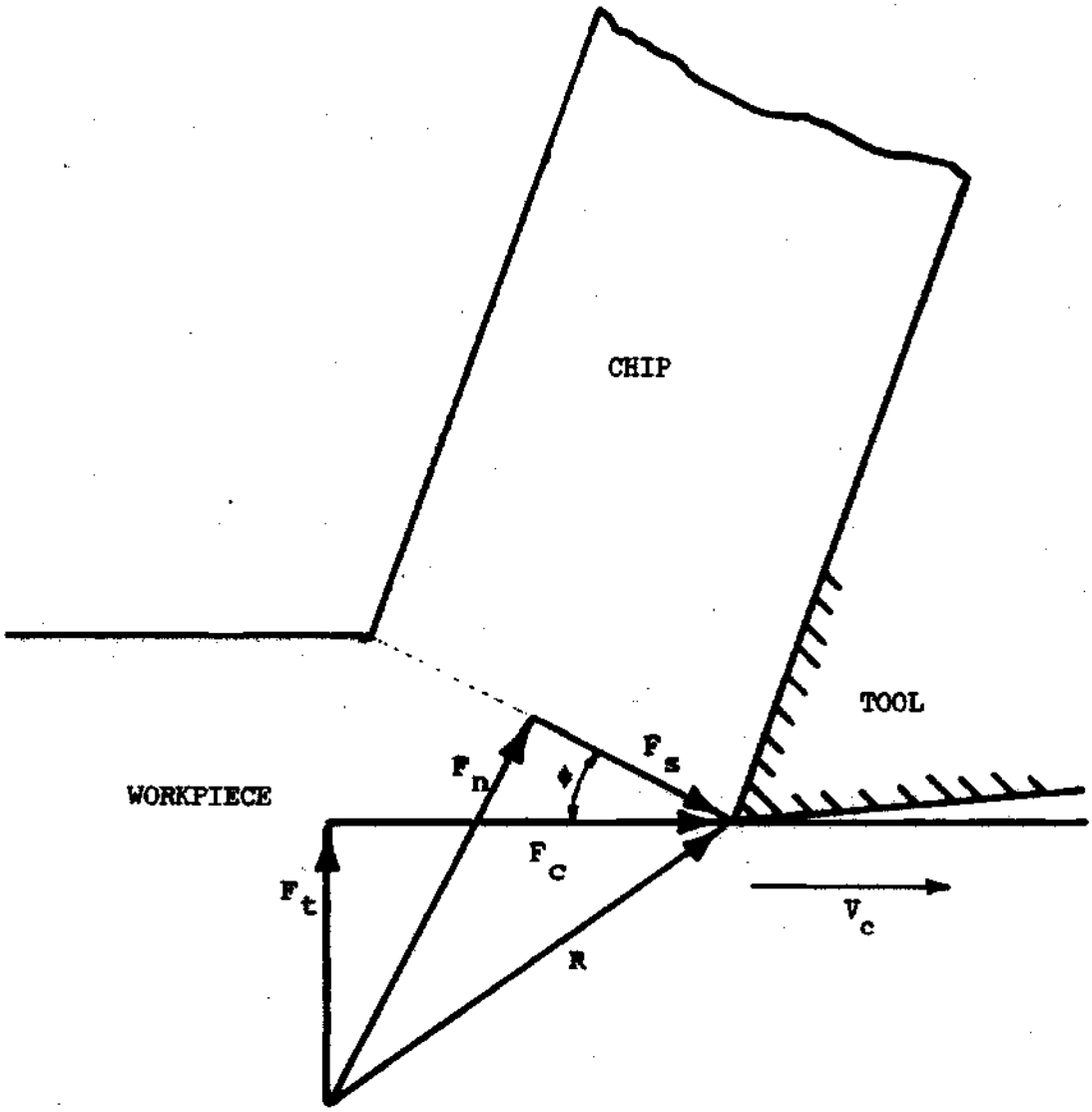


Figure 6: Cutting Forces in Orthogonal Cutting

If the resultant tool force is resolved in a direction parallel to the shear plane, the force F_s required to shear the work material to form the chip is obtained. This force may be expressed in terms of the cutting (F_c) and thrust (F_t) forces, the components of the resultant tool force resolved parallel to, and perpendicular to the direction of relative work-tool motion, respectively. From Figure 5 it can be seen that

$$F_s = F_c \sin \phi - F_t \cos \phi \quad . \tag{6}$$

The shear stress along the shear plane is given by the expression:

$$S = \frac{F_s}{w\, l_s} \text{ psi} \quad , \tag{7}$$

where l_s is the length of the shear plane.

From Equation (5) and Equation (6)

$$S = \frac{(F_c \sin \phi - F_t \cos \phi) \sin \phi}{w\, t_1} \text{ psi} \quad . \tag{8}$$

Much previous work has shown that S, calculated from Equation (8), remains constant for a given work material over a wide range of cutting conditions. However, it has been observed that S increases with a decrease in feed, (t_1). This can be explained by the existence of a tool nose force, P. If P is subtracted from the resultant cutting force R, then the apparent shear strength of the work material remains constant with respect to changes in undeformed chip thickness. Thus, the apparent shear strength of the work material may be said to be constant and a property of the work material, and independent of cutting conditions.

Chip Thickness

The chip thickness, (t_2), is not defined by the geometry of the cutting tool and the undeformed chip thickness, (t_1). It is in this respect that the cutting process differs fundamentally from other metal forming processes where the final shape of the deformed material is determined by the shape of the tool. It is this lack of control of chip thickness which has made analysis of the cutting process extremely difficult, since before any prediction of cutting forces can be made the chip thickness (t_2) must be known.

It can be seen from Equation (4) that a knowledge of chip thickness (t_2) will allow the shear angle (ϕ) to be determined for a given set of cutting conditions. Experimentally, it has been found that the cutting ratio (r_c), and hence the shear angle (ϕ), depend on the work and tool materials and the cutting conditions. A number of attempts have been made in the past to establish a relationship which can be used to predict the shear angle from a knowledge of t_1 and t_2.

Regions of Interest

The principal regions of interest in the orthogonal metal cutting process are illustrated in Figure 3. These are:

1. The primary deformation zone where the work material is continuously sheared to form the chip.

2. The tool nose region where the effect of friction between the tool flank and the newly generated workpiece surface and the ploughing effect of the tool edge are thought to combine to produce a force acting on the tool which does not contribute directly to chip production. (Tool

nose force.)

3. The secondary deformation zone where large chip-tool frictional forces can cause further deformation of the chip material.

Much of the published work on the mechanics of the metal cutting process has been concerned with deformation in the primary deformation zone. A number of analyses have appeared based on a "shear plane" model of the cutting process. The most important of these will now be considered.

Review of Cutting Theories

Theory of Ernst and Merchant

The first complete analysis resulting in a so-called "shear angle solution" was presented by Ernst and Merchant[1]. The model of the cutting process used by these authors is shown in Figure 7. For convenience, the resultant tool force (R) is shown acting at the tool cutting edge and is resolved into components $\bar{N}$ and F in directions normal to and along the tool rake force, respectively, and into components F_n and F_s, normal to and along the shear plane, respectively. The cutting (F_c) and thrust (F_t) components of the resultant tool force are also shown. It is assumed that the entire resultant cutting force is transmitted across the chip-tool interface and that no force acts on the tool edge or flank (i.e., the tool nose force P is zero and the tool is perfectly sharp).

The basis of Ernst and Merchant's theory was the suggestion that the shear angle, ϕ, would assume such a value as to make the work done per unit time in cutting a minimum. Since the work done in cutting is proportional to F_c it was necessary to develop an expression for F_c in

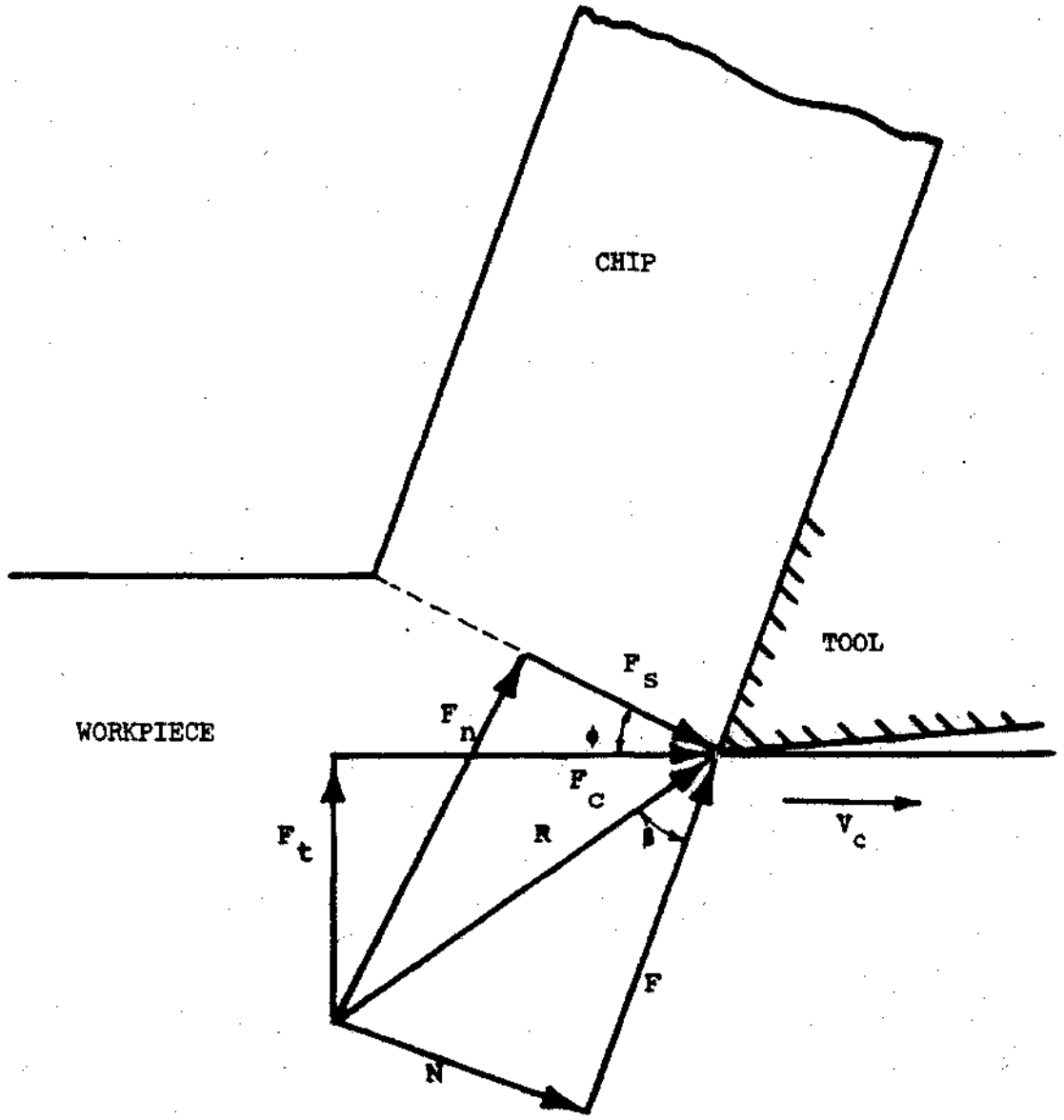


Figure 7: Ernst and Merchant Orthogonal Cutting Model[1,2]

terms of ϕ and then to obtain the values of ϕ for which F_c was a minimum.

It can be shown from Figure 5 that

$$F_c = \frac{S\, A_o \cos(\beta-\alpha)}{\sin \phi \cos (\phi+\beta-\alpha)} \quad , \tag{9}$$

where S is the shear stress on the shear plane, A_o is the cross sectional area removed during cutting, β is the friction angle, α is the rake angle, and ϕ is the shear angle. Equation (9) may now be differentiated with respect to ϕ and equated to zero to find the value of ϕ for which F_c is a minimum. The required value is given by:

$$2\phi + \beta - \alpha = 90^o \quad . \tag{10}$$

Merchant[2] found that this theory gave good agreement with experimental results obtained when cutting synthetic plastics but gave poor agreement for steel machined with a sintered carbide tool. In differentiating Equation (9) with respect to ϕ, it was assumed that A_o and S would be independent of ϕ. Merchant attributed the poor agreement between theory and experiment in the machining of steel to the fact that large normal stresses are transmitted across the shear plane and that these could affect the shear stress on the shear plane. Accordingly, Merchant included in a new analysis the relationship:

$$S = S_o + K S_n \quad , \tag{11}$$

where S_n is the normal stress on shear plane, K is a constant for the material, and S_o is the value of S when S_n is zero.

This indicates that the shear strength of the material increases linearly with increases in normal stress across the shear plane (Figure 8). The value of S is affected by changes in S_n and may be inserted in Equation (9) to give a new equation for F_c in terms of ϕ, namely:

$$F_c = \frac{S_o A_o \cos(\beta-\alpha)}{\sin\phi \cos(\phi+\beta-\alpha) [(1-K) \tan(\phi+\beta-\alpha)]} \quad . \tag{12}$$

If it is now assumed that K and S_o are constants for the particular work material, and that A_o and α are constants for the cutting operation, Equation (12) may be differentiated and equated to zero to give the new value of ϕ. The resulting relationship is

$$2\phi + \beta - \alpha = C \quad , \tag{13}$$

where the machining constant (C) is $\cot^{-1}K$, where K is the slope of Shear Stress versus Normal Stress curve, as shown in Figure 8.

Theory of Lee and Shaffer

The theory of Lee and Shaffer[5] was the result of an attempt to apply plasticity theory to the problem of orthogonal metal cutting. In dealing with problems in plasticity theory it is necessary to make certain assumptions regarding the behavior of the work material when deformed. Some of these assumptions are:

1. The workpiece behaves as perfectly plastic material, i.e., it does not workharden and any elastic deformation can be neglected.

2. The material is rigid up to its yield point and the effects of variations in strain rate and temperature can be neglected.

These assumptions imply a stress-strain curve for the work material of

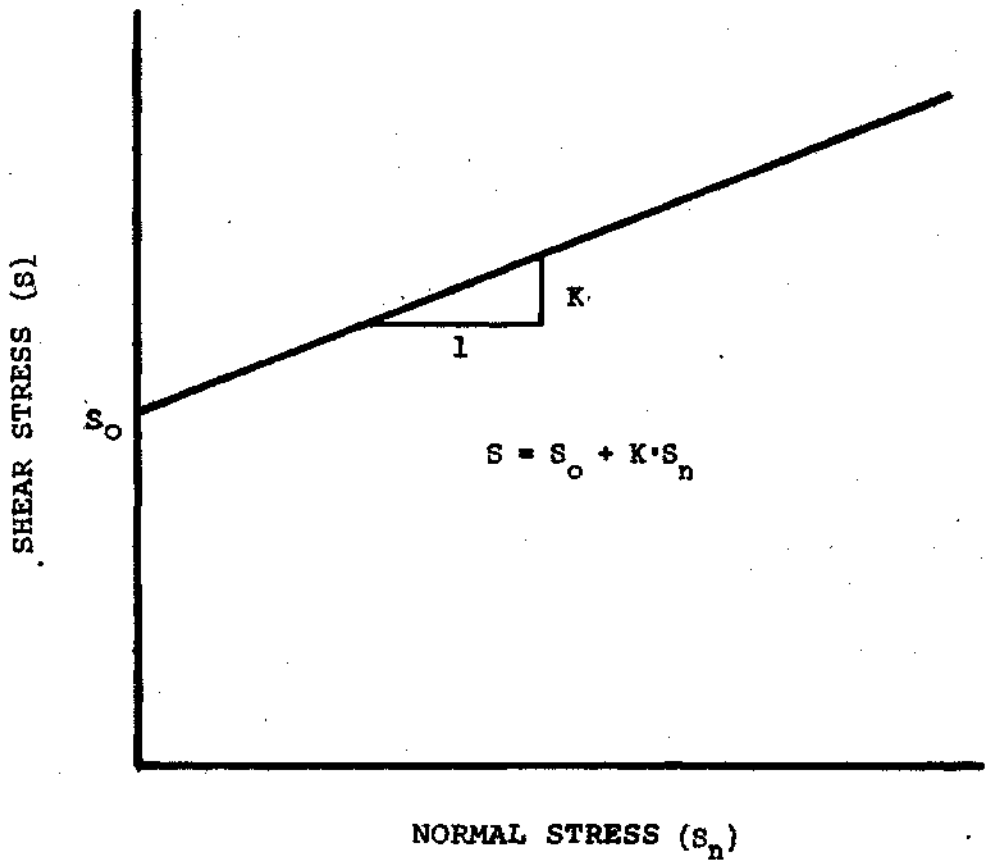


Figure 8: Shear Stress vs. Normal Stress on Shear Plane

the form shown in Figure 9, where the material undergoes no strain until the yield point is reached, when it yields at constant stress throughout the entire deformation process. Such assumptions have led to useful solutions of many problems in metal working.

It is known that the rate of workhardening of many metals decreases rapidly with increasing strain and that the effect of a high strain rate is to raise the yield stress of the metal with respect to its ultimate strength. Thus, with the high strains and strain rates known to exist in metal cutting, the material may approach the ideal plastic condition. Further, with the high plastic strains, the elastic strain would form a negligible proportion of the total strain. Thus, the stress-strain curve for the work material could approximate the ideal case shown in Figure 9.

In the solution of problems in plasticity, the construction of a slip line field is necessary; this consists of two orthogonal sets of lines (called slip lines) indicating, at each point in the plastic zone, the two orthogonal directions of maximum shear stress.

The slip line field proposed by Lee and Shaffer[5] for orthogonal cutting with the production of a continuous chip with the absence of a built-up edge on the tool face is shown in Figure 10. It can be seen that Lee and Shaffer have employed the idealized shear plane model of the cutting process where all the deformation takes place in a plane extending from the tool cutting edge to the point of intersection of the free surfaces of the workpiece and chip. From Figure 10 it can be shown that:

$$\phi + 45^{\circ} + \beta - \alpha = 90^{\circ} \quad , \qquad (14)$$

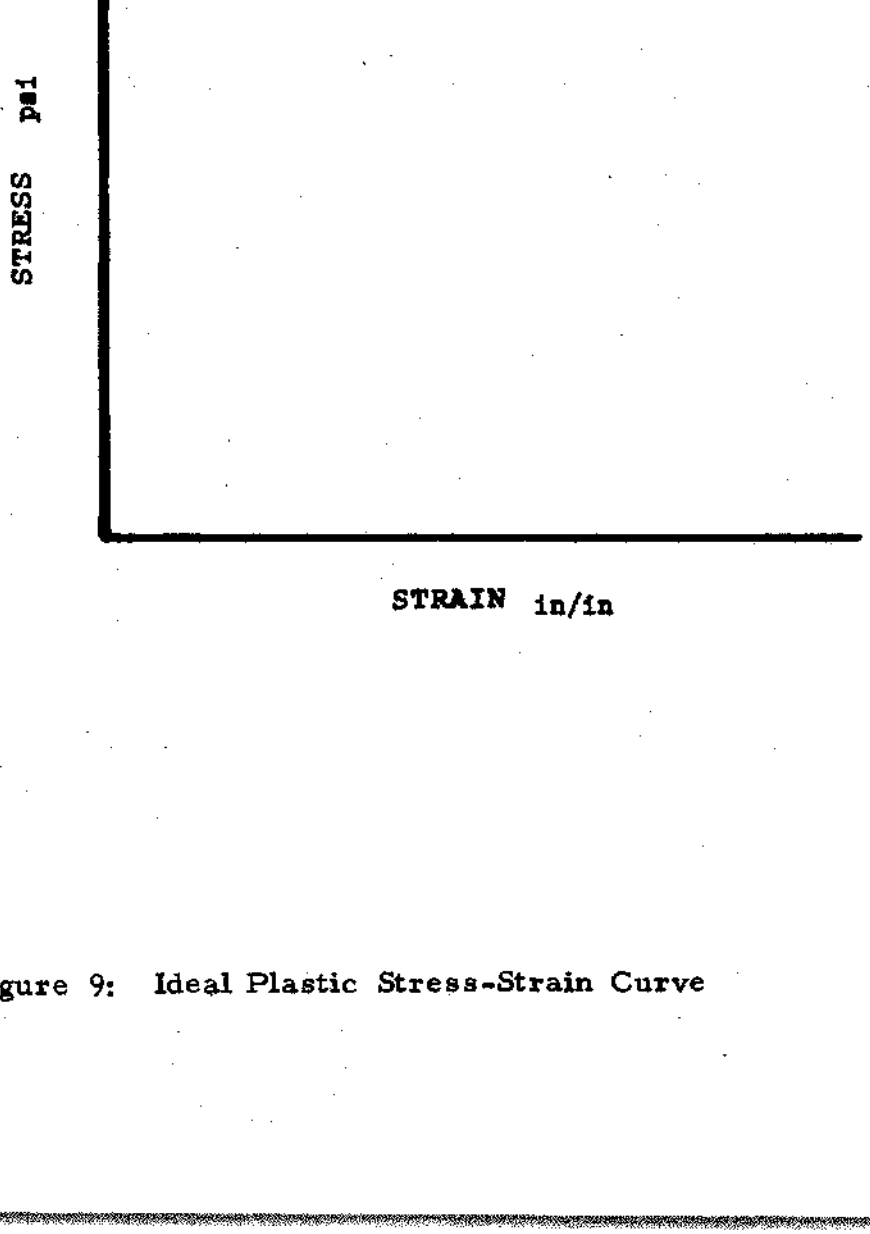


Figure 9: Ideal Plastic Stress-Strain Curve

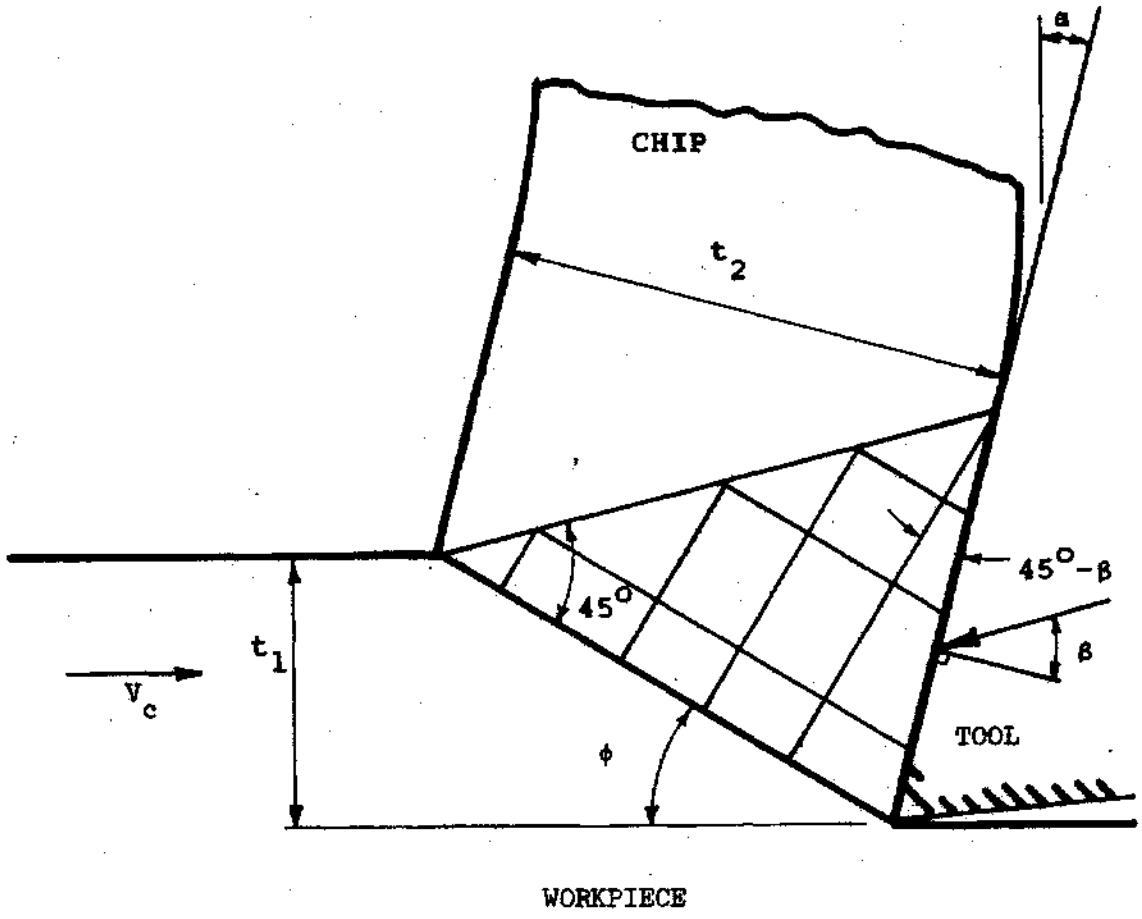


Figure 10: Lee and Shaffer Slip Line Field Solution

or

$$\phi + \beta - \alpha = 45^{\circ} \quad , \tag{15}$$

which is the required shear angle solution.

Lee and Shaffer[5] realized that Equation (15) could not apply where β is 45° and α is 0° since with these values ϕ would be equal to zero. The authors considered that conditions of high friction and low tool rake angles were those which could lead to the formation of a built-up edge. In order to account for this, a second solution[5] was presented with a new geometry in which a built-up edge was present on the tool rake face.

Other Shear Angle Theories

In addition to the theories of Ernst and Merchant[1,2] and Lee and Shaffer[5], several other shear angle relationships have been developed. Huck[6,8] proposed the relationships:

$$\phi = 45^{\circ} - \omega + \alpha \tag{16}$$

and

$$\phi = \frac{1}{2} \cot^{-1} C - \beta + \alpha \quad , \tag{17}$$

where ω is given by the expression

$$\omega = \frac{1}{2} \tan^{-1}(2\mu) \quad , \tag{18}$$

where μ is the coefficient of friction and C is the machining constant.

Stabler[7] has proposed the relationship:

$$\phi = 45^{\circ} - \beta + \frac{1}{2}\alpha \quad . \tag{19}$$

Shaw, et al.[9] proposed that the shear plane was not the plane of maximum shear stress and suggested the relationship:

$$\phi = 45^{\circ} + \eta - \beta + \alpha \quad , \tag{20}$$

where η is the angle between the shear plane and the direction of maximum shear stress.

Oxley[13] developed a strain hardening model of chip formation (see also Figure 11 after Palmer and Oxley[18]) in which the shear angle is given by the equation:

$$\phi = \beta - \alpha - \theta \quad , \tag{21}$$

where

$$\theta = \tan^{-1} \frac{P_A + P_B}{2k} \quad , \tag{22}$$

and where P_A and P_B are the hydrostatic stresses at A and B and k is the shear stress along AB (Figure 11).

An important implication of the analysis of Oxley[13] and Palmer and Oxley[18] is the existence of a tensile stress at the nose of the tool and the extension of the plastic zone below the nose of the tool. Variable flow stress properties of the workpiece material were considered by Oxley[33-37] in an extensive analysis of a shear zone which was wide in proportion to its length. In these analyses estimates of the forces involved during cutting were made for various cutting speeds.

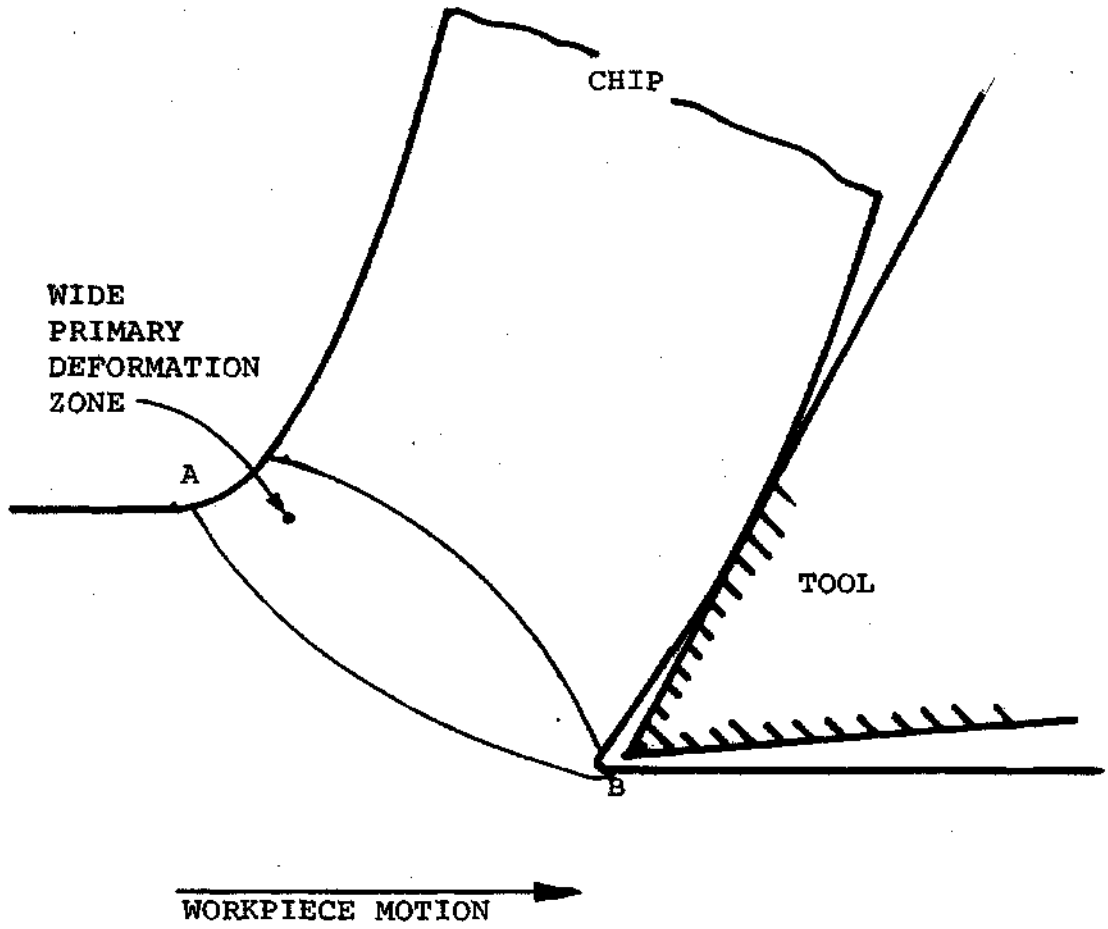


Figure 11: Palmer and Oxley Model

A minimum energy solution for the shear plane angle was developed by Rowe and Spick[38]; however, the simplifying assumptions involved provide little further advancement and the minimum energy criterion as applied to the metal cutting process is also open to question.

Several other shear angle relationships have been developed including those by Weisz[6,10], Colding[6,11], Sata and Mizuno[6,12], Kullberg[30], and Zorev[14]. A comparison of some of these has been made by Sata[6].

Theory of Boothroyd

A new approach to the analysis of the mechanics of the orthogonal cutting process under unlubricated cutting conditions has been presented by Boothroyd[24] and Boothroyd and Bailey[15]. The assumptions made in this analysis were:

1. The apparent shear strength of the metal in the primary deformation zone is a constant for the material and is independent of the undeformed chip thickness, tool rake angle, cutting speed, and the work-hardened state of work material.

2. The deformation process is one of plane strain where the effect of side spread of the chip during its formation is neglected.

3. A continuous chip is produced with an absence of a built-up edge on the tool face.

4. The work material is a single phase metal whose behavior at high strains and at different strain rates and temperatures may be represented qualitatively by the curve shown for aluminum in Figure 12 (after Bailey)[16].

5. The cutting process is not lubricated either by the application of a fluid or through the presence of inclusions of a lubricating nature

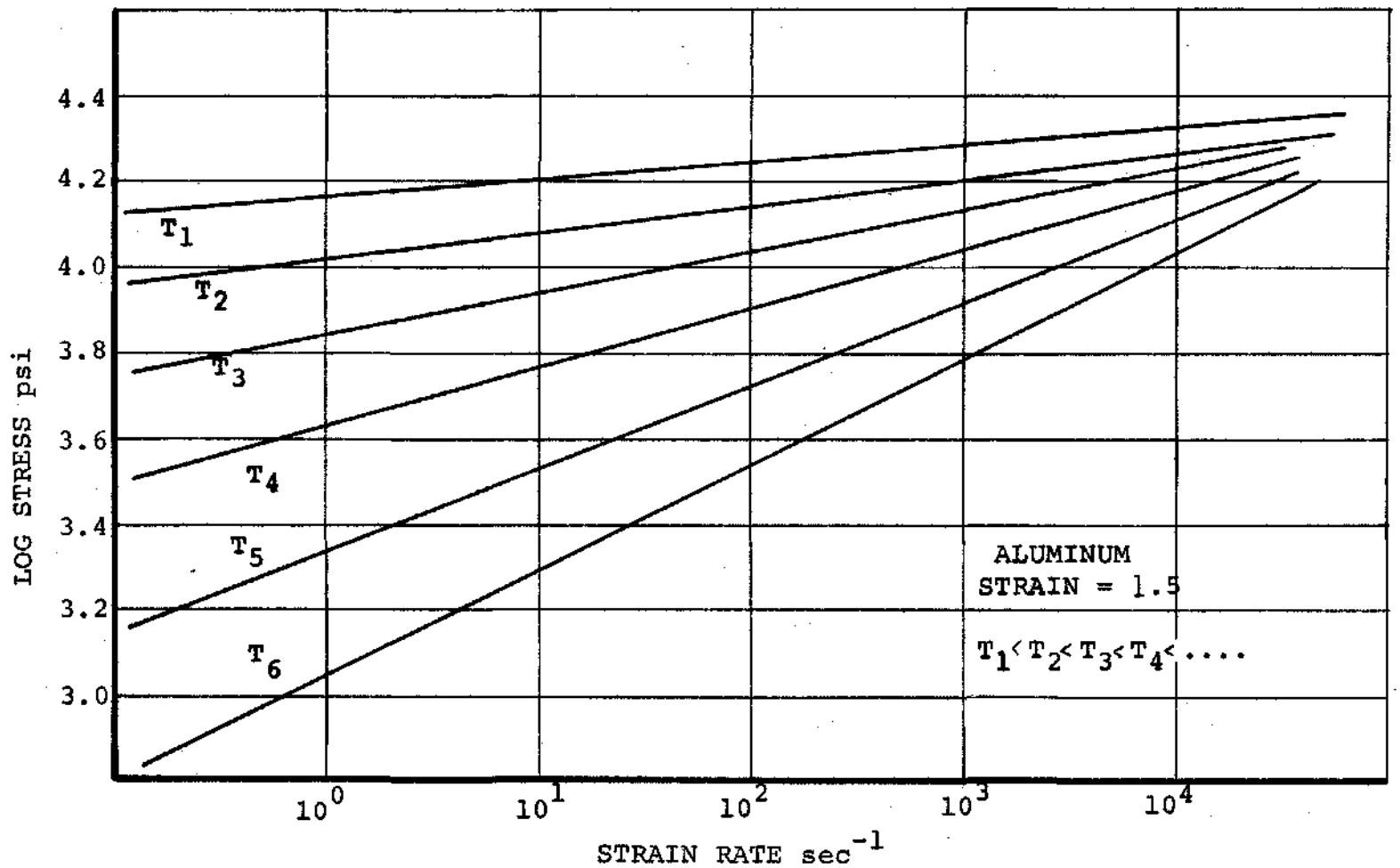


Figure 12: Stress, Strain Rate, Temperature Relationship For Aluminum[16]

in the workpiece.

From a force analysis of the model[15] it was shown that the dimensionless stress ratio, $\frac{S_s}{S_o}$, was given by the expression:

$$\frac{S_s}{S_o} = \frac{(1+\tan \Psi) \tan(\gamma-\alpha) - (1-\tan \Psi)}{1 + \tan^2(\gamma-\alpha)} \quad , \tag{23}$$

and the ratio $\frac{S_f}{S_o}$ by:

$$\frac{S_f}{S_o} = \frac{(1+2 \tan \Psi) \tan \beta}{1 + 2 \tan \beta - \tan \alpha} \quad , \tag{24}$$

where β is the mean angle of friction and the remaining angles are defined in Figure 13; the stress S_s is the shear stress along the line AB in Figure 13 and is that stress obtained at a high strain rate for a highly strained material; the stress S_o is the shear stress along line BE obtained at much lower strain rate; the stress S_f is the shear stress along the tool rake face and may be higher, lower, or equal to the shear stress (S_o) on line BD.

From cutting test data on 85-15 Brass, $\frac{S_s}{S_o}$ was found to be a constant for the work material and independent of changes in rake angle or cutting speed. The ratio $\frac{S_f}{S_o}$ was found to vary with rake angle and cutting speed and was controlled by the conditions of strain rate and temperature at the tool rake face.

Critique of Existing Work

Two of the shear angle solutions outlined above have been compared with the results of independently conducted experiments[17]. Figure 14

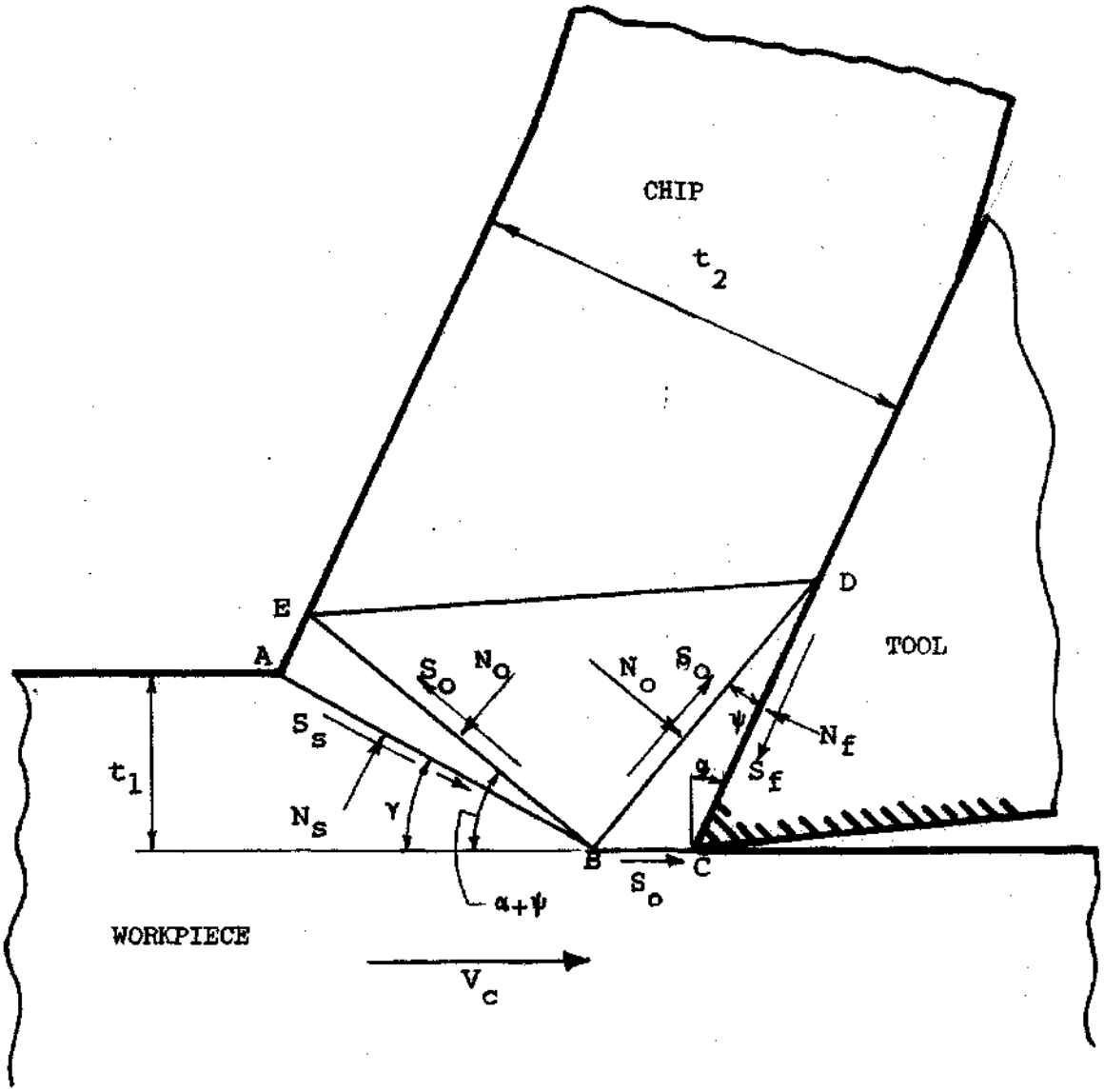
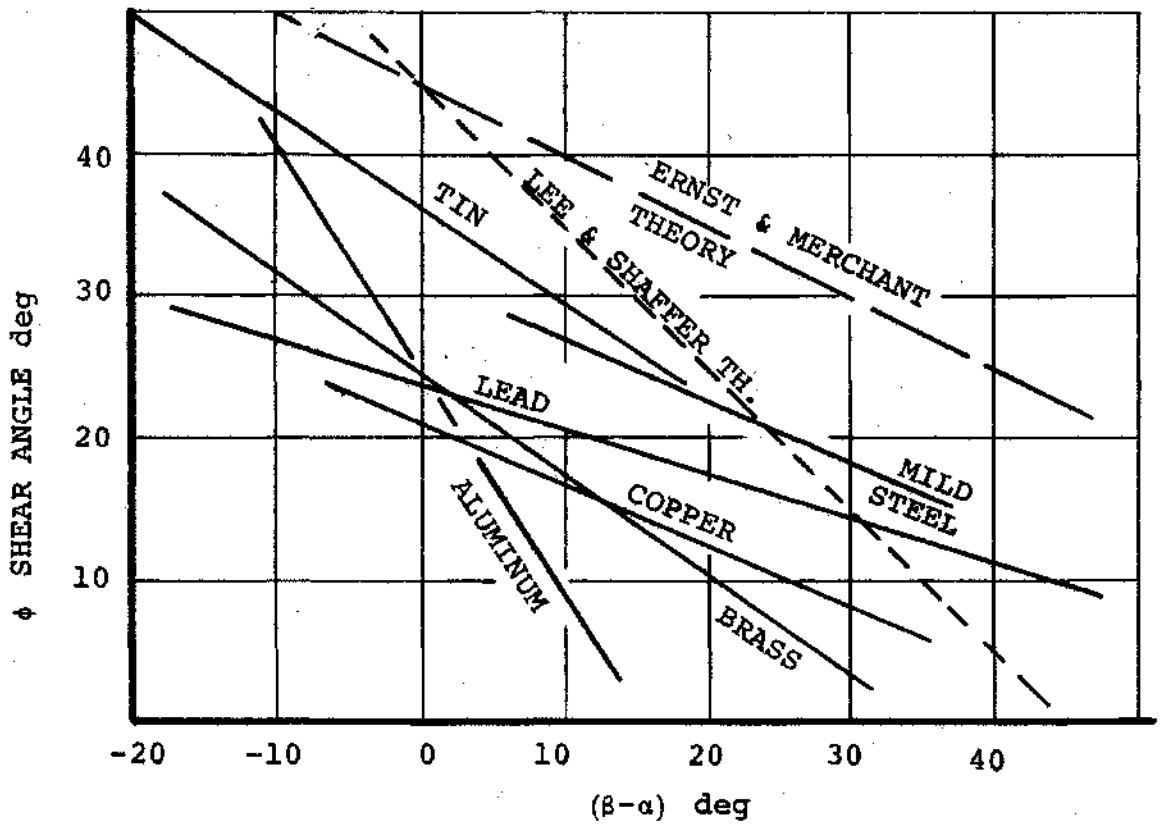


Figure 13: Model Used by Boothroyd[15] to Predict Brass Cutting Results



β = MEAN ANGLE OF FRICTION
α = RAKE ANGLE

Figure 14: Some Theoretical and Experimental Shear Angle Relationships

shows the most convenient way of making such comparisons; the shear angle ϕ is plotted against the difference between the friction angle and the rake angle; i.e., $(\beta-\alpha)$. On such a graph, the relationships obtained by the Ernst and Merchant and by the Lee and Shaffer theories form straight lines. It can be seen that neither of these theories approach quantitative agreement with any of the experimental relationships for the various materials tested. However, comparing them in a qualitative sense, both the theories and the experimental results show that a linear relationship exists between ϕ and $(\beta-\alpha)$ and that a decrease in $(\beta-\alpha)$ always results in an increase in ϕ. For a given rake angle a decrease in the mean friction angle on the tool rake face results in an increase in the shear angle. Since the mean shear strength of the work material along the shear plane is approximately constant, the force required to form the chip will be reduced and a corresponding reduction in shear plane length will occur.

The results plotted in Figure 14 shows that no unique relationship of the kind predicted by the Ernst and Merchant[1] and by the Lee and Shaffer[5] theories could possibly agree with all the experimental results. Even the modified Merchant theory[2] in which the shear stress on the shear plane is assumed to be linearly dependent on the normal stress could not agree with all the results. Substituting various values for the machining constant in Equation (13) could only give a series of parallel lines on the graph in Figure 14. Clearly, the experimental lines are not parallel and could not all be represented by Equation (13). It is for this reason that other attempts have been made to develop machining constants for individual materials; usually they have met with little success.

Recent work[18,19] has also shown that the range over which the

primary deformation zone can be regarded as a shear plane is not as large as it had been thought previously. For example, Palmer and Oxley[18] used motion pictures to observe the flow of grains in a steel workpiece during slow speed cutting. Their investigation showed that the primary deformation zone had the form shown in Figure 11. Work by Nakayama[19] has also shown the primary deformation zone to be wide and to have constant proportions for cutting speeds of up to 500 feet per minute. In these experiments the side of the workpiece was coated with lamp black and a series of lines were scribed on the prepared surface parallel to the cutting direction. During cutting, these lines formed stationary material flow lines and could be photographed. From the resulting photographic records it was possible to plot the boundaries of the primary deformation zone.

The above shear angle theories and the experimental results indicate that the friction on the tool rake face is a most important parameter in metal cutting,and in virtually all the theories produced to date the simplifying assumption has been made that frictional condition on the tool face can be represented by a single parameter, the mean angle of friction β.

The theory proposed by Boothroyd and Bailey[15] does have direct application to the machining of 85-15 Brass and to a certain degree predicts the geometry and forces of cutting for that one material. However, when application to the machining of aluminum was attempted by this author, unsatisfactory results were obtained. Certain other limitations in previous analyses have been observed, namely:

1. Most authors completely neglect secondary deformation.

2. Under certain cutting conditions the secondary deformation zone extends below the tool nose into the workpiece[18].

3. A velocity flow diagram of most of the previously defined models is inconsistent. It is not reasonable to expect material to change its direction of motion instantaneously as it passes the shear plane. In this respect the analyses by Boothroyd and Bailey[15,24] and Oxley[34-37] are definite advancements over the shear plane type analyses.

4. The normal stress on plane BE of the Boothroyd model is not necessarily small and for materials which exhibit large secondary deformation zones may be large.

5. A velocity flow diagram of the Boothroyd model in the secondary deformation zone is inconsistent.

Thus, it is evident that an improved model of the orthogonal metal cutting process is needed.

CHAPTER III

EXPERIMENTAL PROCEDURE

Introduction

An aluminum (1100 - O) tube was orthogonally end-machined on a lathe using a two component, strain gage, cutting force dynamometer. The dynamometer output was amplified and recorded on a two-channel pen recorder. The undeformed chip thickness was measured with a ball-end micrometer and verification made by weighing a known length of chip and neglecting the small amount of side spread of the chip. The tool rake angle was varied through use of replaceable HSS tool inserts rigidly mounted in the dynamometer. The rake angle was measured with a tool maker's microscope. Tools were ground with a small tool and cutter grinder.

Equipment

The design of the metal cutting dynamometer used in these experiments is based on one described by Boothroyd[47]. Improvements were made in the method of supporting the tool and in the strain gage Wheatstone Bridge arrangement. The dynamometer tool holder was so designed that it supported a 3/8-inch square HSS tool at a 45 degree angle from the vertical. The tool was held rigidly against the dynamometer by two set screws which were recessed into the toolholder. Tools of various rake angles were produced by grinding the tool surface inclined from the horizontal at the appropriate rake angle. An appropriate flank relief angle of five degrees was ground on each tool. The tool and the functional por-

tions of the dynamometer are shown in Figure 15.

Strain gages were mounted on the horizontal and vertical struts of the dynamometer in such a manner as to negate the effects of bending of the strut and give a change of resistance proportional to compressive stress within the strut. Temperature compensation was accomplished by mounting strain gages on the reverse side of each strut perpendicular to the direction of loading. These compensating gages also increased the sensitivity of the dynamometer by adding the effect of the strain due to Poisson's ratio to the net effective difference in resistance across the measuring terminals of the Wheatstone bridge. The position of the strain gages on the struts and in the Wheatstone bridge was such that a variation in the position of the tool and consequent change of moment resisted by the dynamometer did not affect the bridge output. A layout of gage positions and a schematic diagram of gage placement in a Wheatstone bridge for one component of the forces of cutting is shown in Figure 16.

A sketch of the set-up used on the 15" x 60", 5 horsepower, variable speed Cincinnati lathe is shown in Figure 17. The output of the dynamometer was amplified by a Sanborn Model 366-1100-B carrier preamplifier and recorded on a Sanborn Model 296 dual-channel recorder. The gain of the preamplifier was adjusted so that a 1 volt change across each bridge resulted in a 30 mm. deflection of the associated recorder pen.

Calibration of the dynamometer was accomplished by a dead weight loading technique and showed excellent linearity and very little interchannel interaction for the dynamometer-recorder system. This procedure has been described in the literature[47].

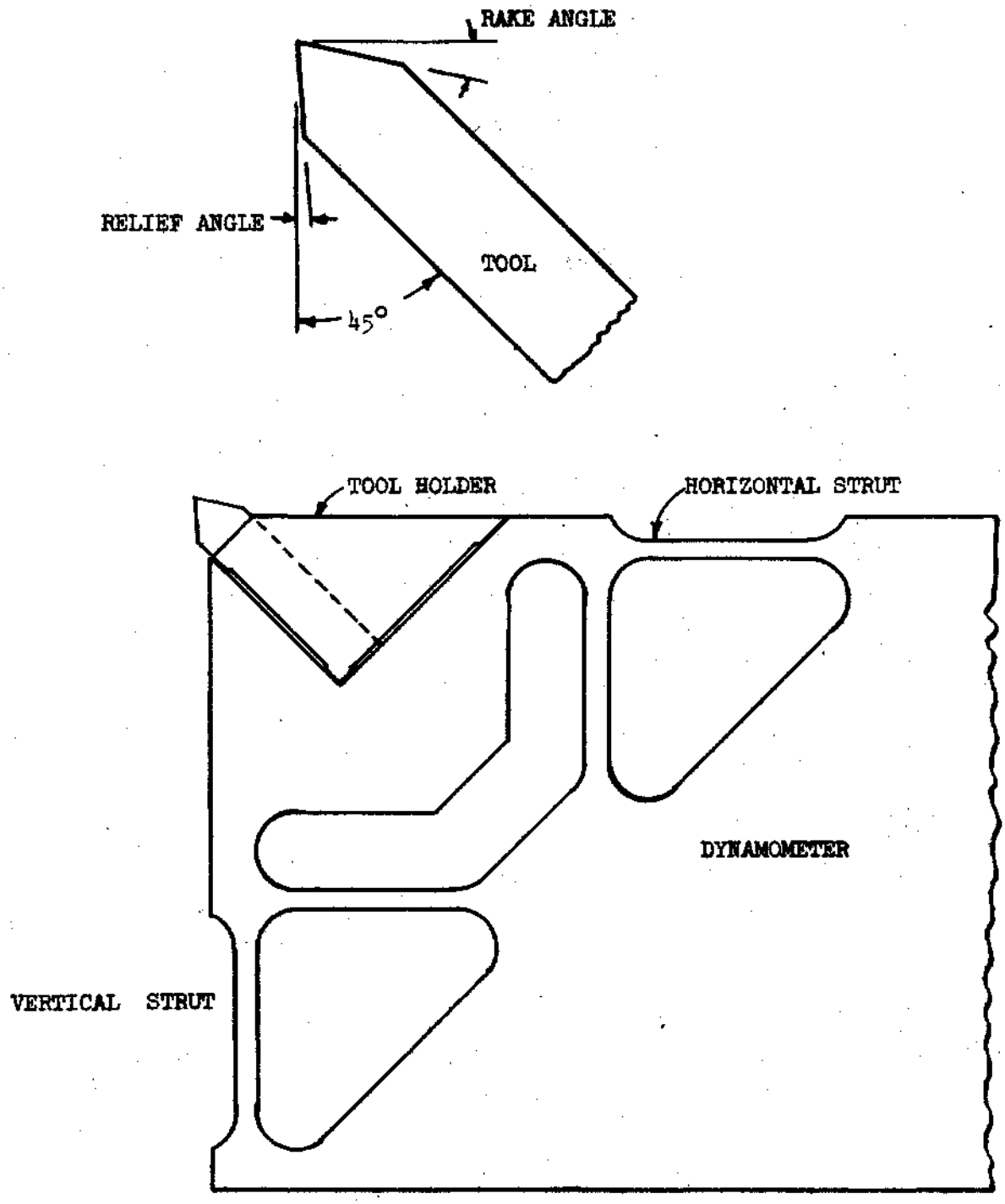
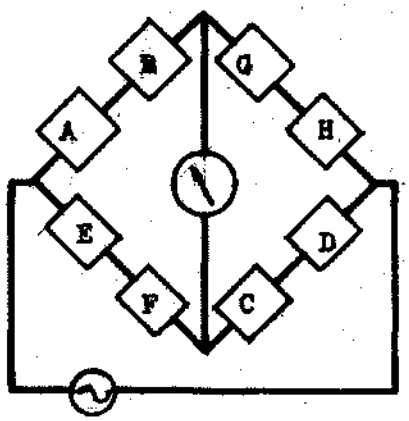
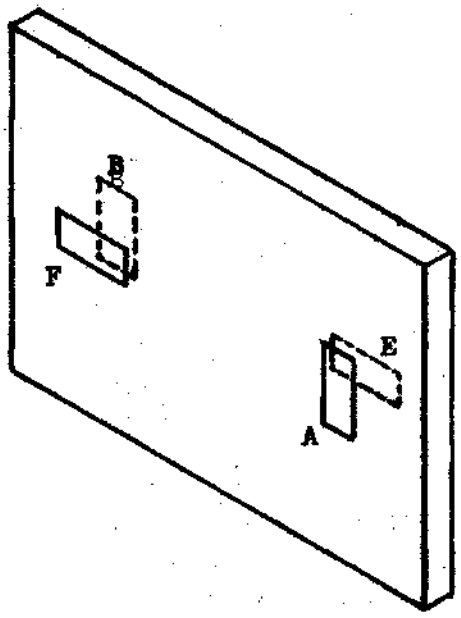
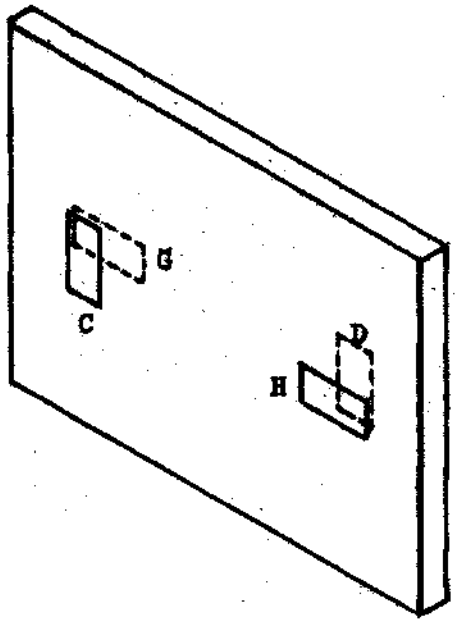


Figure 15: Dynamometer Configuration



SCHEMATIC





ACTIVE STRAIN GAGES	COMPENSATING STRAIN GAGES
A	E
B	F
C	G
D	H

Figure 16: Strain Gage Layout and Schematic for Vertical Force Component of Dynamometer

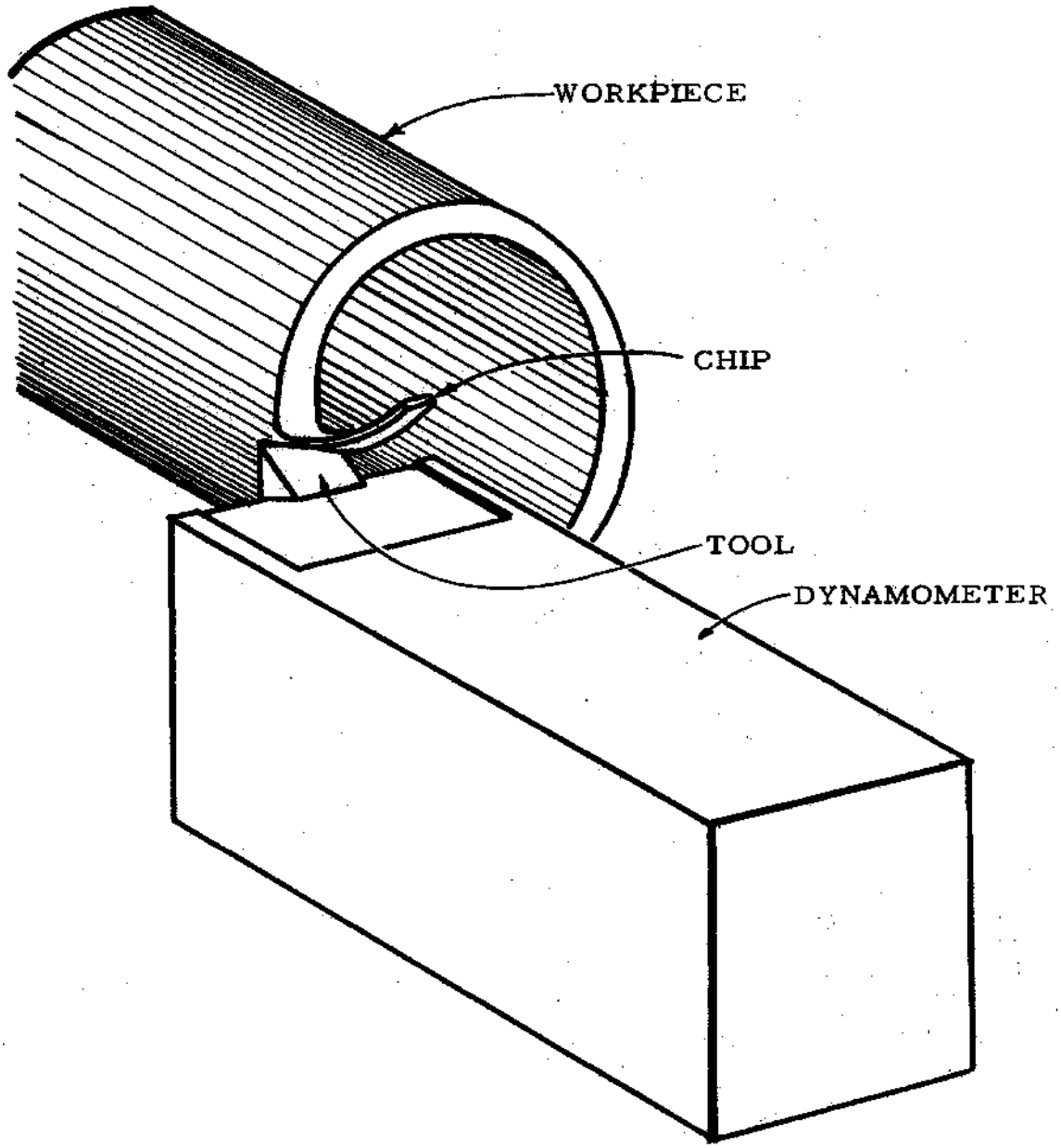


Figure 17: Workpiece With Dynamometer

Procedure

Orthogonal machining was realized by end machining a 3 inch outside diameter tube with a 0.28 inch wall thickness. The tube was produced by machining a solid aluminum billet to the required dimensions in the Cincinnati lathe. The cutting tests performed were chosen to cover the entire range of cutting conditions possible within the material and equipment limitations. An undeformed chip thickness of 0.0202 inches was chosen because this was the minimum value which would give good delineation between the cutting and thrust force for a variety of cutting speeds.

The maximum cutting speed was 480 SFPM because higher speeds required more power than the lathe motor could provide. The minimum cutting speed was 80 SFPM because the chip produced at lower speeds tended to be discontinuous or irregular with a built-up edge.

The maximum rake angle was 45 degrees. To exceed this would seriously weaken the tool and result in direct rubbing contact between the chip and the toolholder leading to extraneous dynamometer output and negation of the experimental results. The minimum rake angle used was approximately 20 degrees. Results of the tests with this rake angle are questionable because of irregularities in chip thickness and the presence of an unstable built-up edge on the rake face. The results of these tests will be included in the analysis, however, in spite of the questionable continuity of cutting conditions. Therefore, variations of results of this rake angle with predictions of the model may be expected. Nominal rake angles of 20, 25, 30, 35, 40, and 45 degrees and velocities of 80, 120, 160, 240, 320, and 480 SFPM were used in the work. Cutting

speeds in SFPM were determined from the product of the average circumference of the tubular workpiece and the angular velocity of the lathe as measured by the lathe tachometer. The recorded experimental data of this series of orthogonal metal cutting tests were the cutting and thrust forces and the chip thickness. Smoothed values of these results are tabulated in Table 2 (shown in Appendix I) where an averaging of several test points was made in order to prevent excessive experimental error.

A series of controlled contact length experiments was also performed in order to ascertain the magnitude of the tool nose forces. The tool nose forces result from the ploughing effect of the tool and friction between the tool flank and freshly machined workpiece surface. The controlled contact length resulted in a similar geometry of cutting for a variety of undeformed chip thicknesses when the ratio of contact length to undeformed chip thickness was maintained constant. Tool nose forces were calculated by extrapolating the total cutting tool forces to zero undeformed chip thickness.

Typical results of this investigation for a single set of cutting conditions are shown in Figures 18 and 19. These figures indicate that the tool nose force (as determined by the zero undeformed chip thickness) is of sufficiently small magnitude to neglect its effects when performing cutting tests with a t_1 value greater than 0.020 inches. (Sufficiently small magnitude being less than the resolution of the pen recorder for the thrust force, i.e., 1/2 mm or 10 pounds thrust force, or 10 percent of the cutting force).

A determination of the microhardness distribution of a suddenly stopped chip specimen was also made and is shown in Figure 20. The iso-

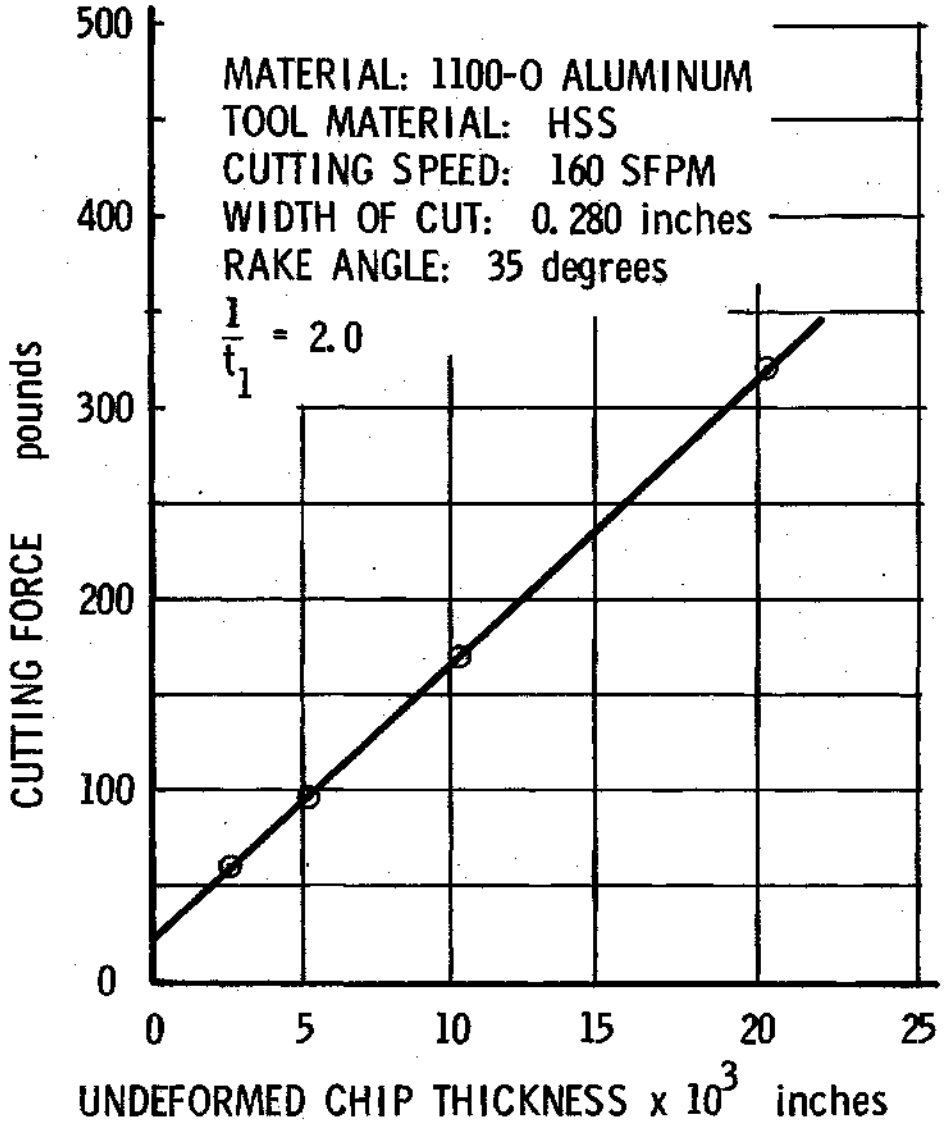


FIGURE 18: CUTTING FORCE vs. UNDEFORMED CHIP THICKNESS

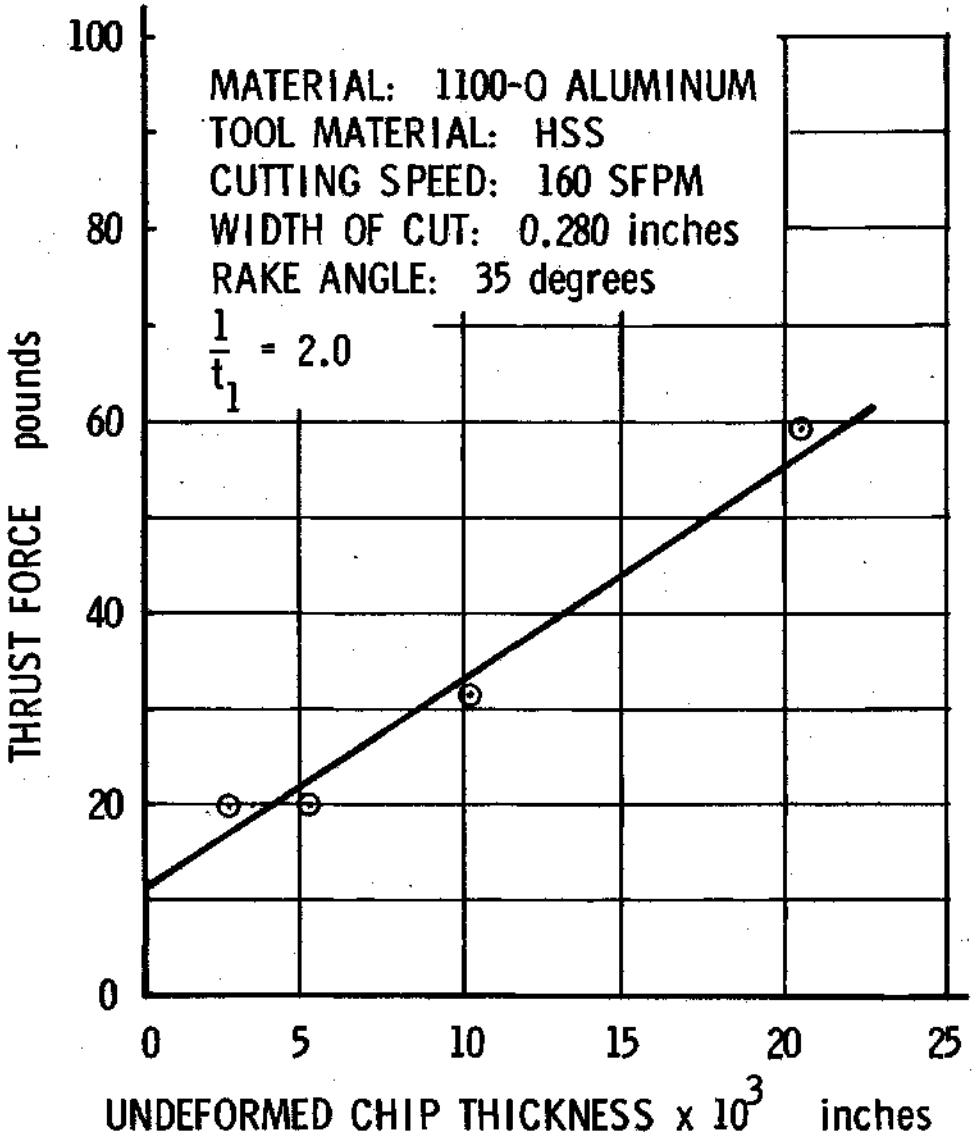


FIGURE 19: THRUST FORCE vs. UNDEFORMED CHIP THICKNESS

MATERIAL: 1100-O ALUMINUM
TOOL MATERIAL: HSS
CUTTING SPEED: 40 SFPM
RAKE ANGLE: 30 DEGREES
UNDEFORMED CHIP THICKNESS: 0.0202 INCHES

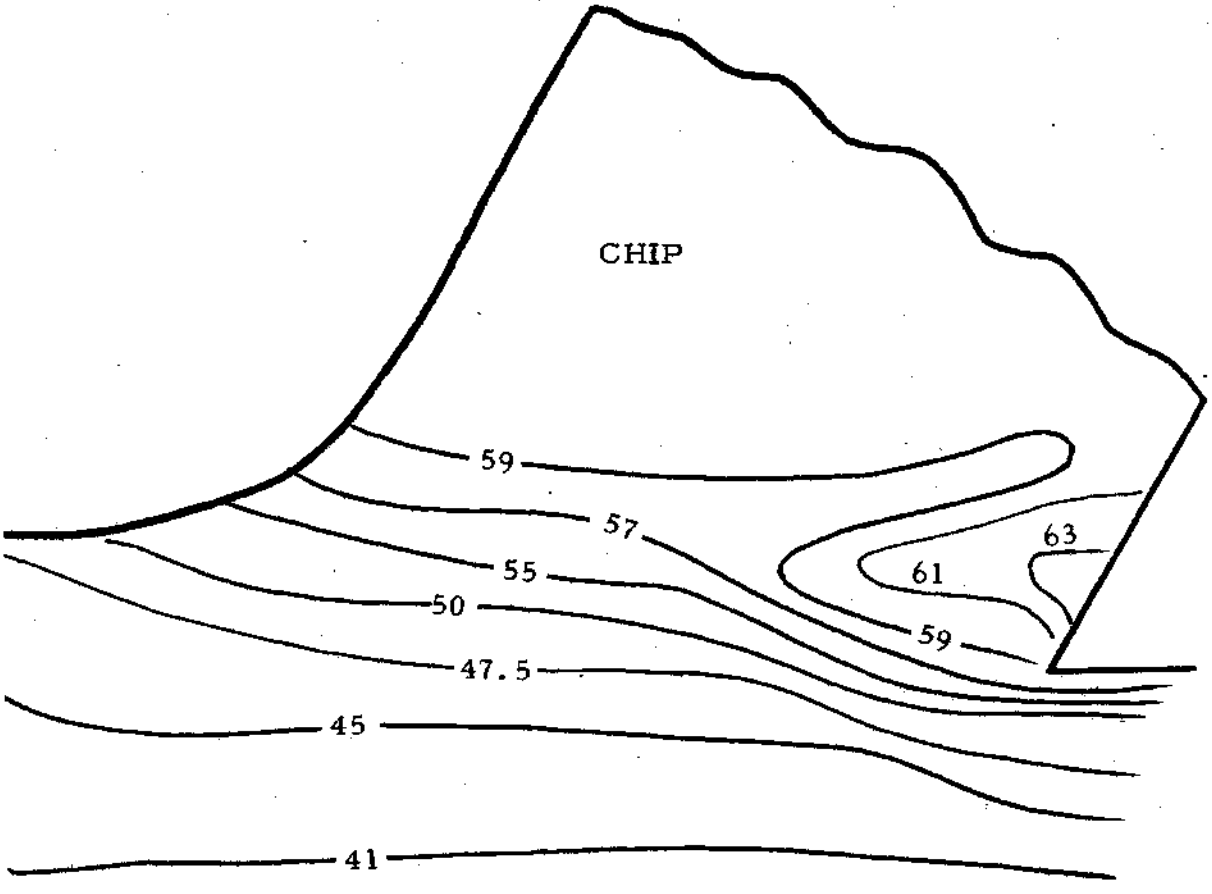


Figure 20: Microhardness Distribution of Suddenly Stopped Chip Sample

grams of equal microhardness give an indication of the amount of work-hardening which has occurred at any specific point. The key quantiative results of the investigation are that the material has been workhardened (therefore deformed) below the freshly machined workpiece surface well ahead of the nose of the tool and that workhardening due to secondary deformation has occurred along the chip-tool interface.

A representation of typical flow lines discernable in a suddenly stopped chip sample which has been polished and etched is given in Figure 21. A photomicrograph of this deformation did not give a sufficiently distinct image to be of value.

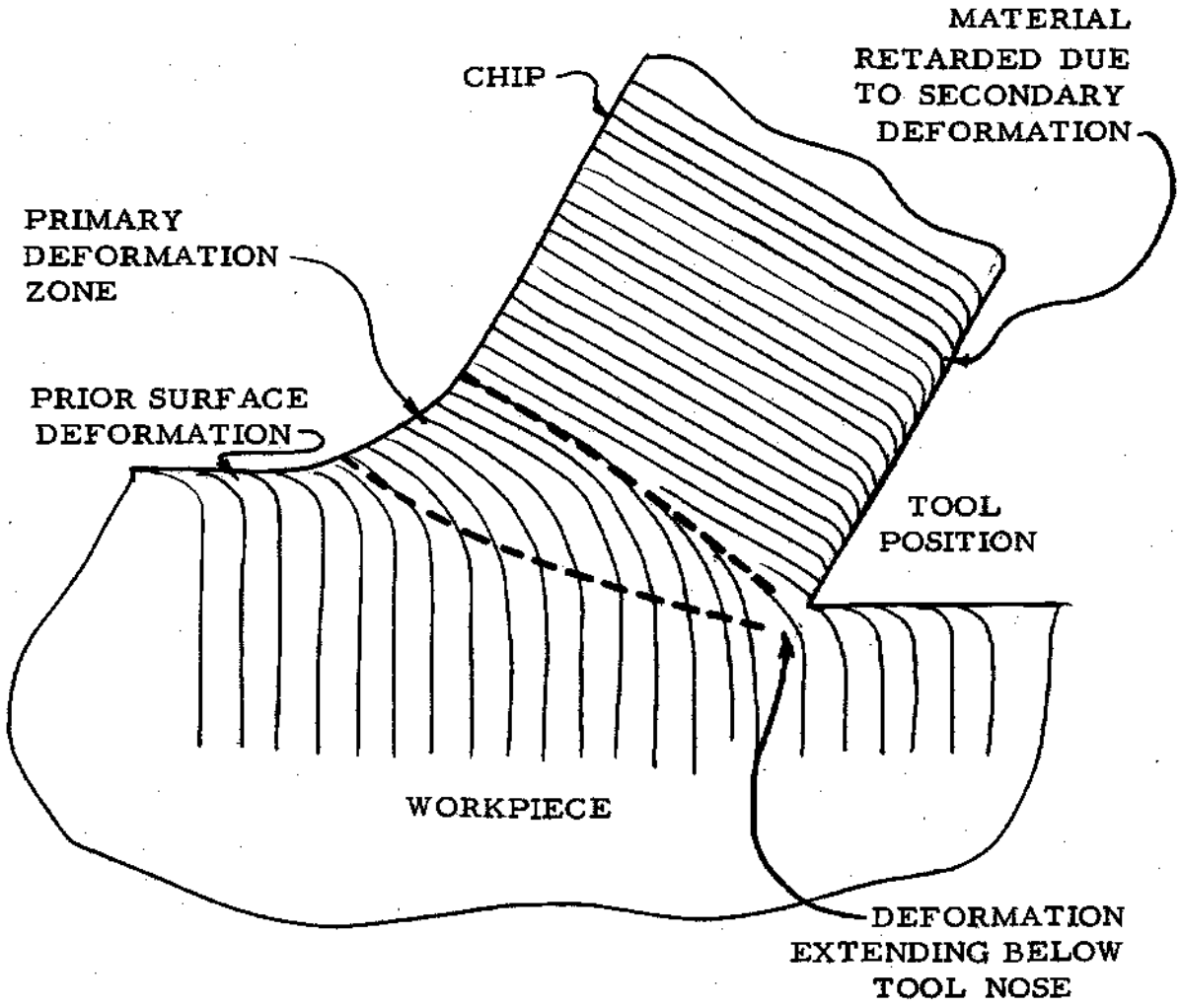


Figure 21: Typical Flow Lines Observed in a Suddenly Stopped Chip Sample

CHAPTER IV

MODEL DESCRIPTION

Introduction

The physical phenomena which occur during the orthogonal metal cutting process are extremely complex. An exact mathematical analysis would require a large number of variables and generally would not be feasible from an engineering viewpoint. Furthermore, the validity of such an analysis would be questionable because the primary criteria available to verify the sum total of all assumptions would be the applicability and accuracy of the model in predicting such parameters as tool forces and cutting geometry for a wide range of cutting conditions. Albrecht[22] stated this principle in the form that the predictability of a model of the metal cutting process increases as the simplicity of the model decreases (the predictability approaching 100 percent as the number of factors considered becomes very large).

The following analysis is a compromise between simplicity and the need for an accurate model as measured by its applicability and the requirement that material deformation occur in a reasonable and logical manner. The deciding criteria for any assumption therefore is that it be reasonable in light of known characteristics of the material and the flow of metal during the orthogonal metal cutting process. The proposed analysis will include most of the important characteristics enunciated by Shaw[23] with the exception of the condition where the built-up edge

occurs, which is usually present only at low cutting speeds and rake angles.

Proposed Model

The proposed model of the orthogonal metal cutting process is shown in Figure 22. The following initial assumptions are made:

1. The deformation process is one of plane-strain, where the effects of side spread of the chip material during deformation are negligible.

2. A continuous chip is formed and no built-up edge exists on the tool rake face.

3. The work material is a single phase metal whose behavior at different strains, strain rates, and temperatures may be represented by an equation of the form

$$\sigma = \sigma_o \, G^T \, \epsilon^{(A+BT)} \, \dot{\epsilon}^{(C+DT+F[\ln\epsilon]T)} \quad , \tag{24}$$

which is similar to that proposed by Lubahn[21].

4. The cutting process is unlubricated, either by the application of a fluid or through the presence of inclusions in the workpiece of a lubricating nature.

In order to perform the analysis, the region in which the chip is formed was divided into several zones for convenience. These zones are as follows (see Figure 22):

1. The zone CGBEA, which is an approximation to the primary deformation zone as it actually occurs in the machining process, zone CGBEA, is divided into two portions by line AB.

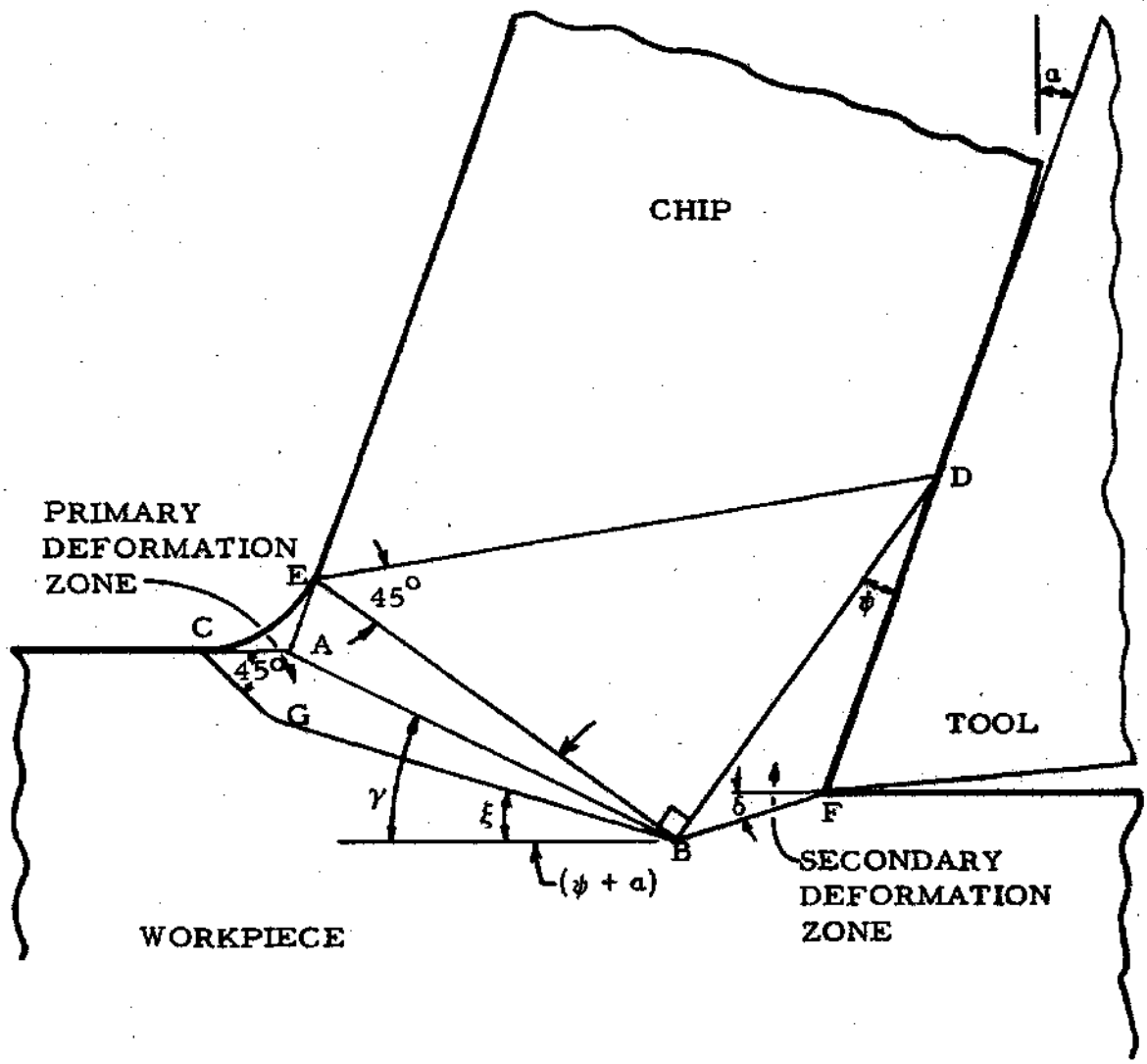


Figure 22. Developed Model of Orthogonal Metal Cutting Process

2. The zone EDB through which stresses are transmitted to the primary deformation zone, but where no deformation occurs.

3. The zone BDF which is an approximation to the secondary deformation zone as it actually occurs and where the chip material is subjected to further deformation due to the high normal and shear stresses at the chip tool interface.

The stresses acting on these individual zones are shown in Figures 23 and 24.

The behavior of the work material as it passes through the various zones is assumed to be as follows.

1. Primary Deformation Zone - CGBEA

Plastic deformation begins at the boundary CGB as the material approaches the cutting tool. The shear stress along CGB is a constant for the workpiece material and is denoted by S_i, the initial shear strength of the work material. Plane CG intersects the free surface of the undeformed workpiece at 45°, at point C. The shear and normal stresses on plane CG are assumed to be of equal magnitude and plane BG is assumed to be of a length equal to that of plane AB. (This may be in slight error but a 10 percent change in the length of plane BG was found to have a negligible effect on the resulting model geometry.)

After crossing surface CGB the material is deformed by a process of shear at a rapidly increasing rate until it reaches the plane AB, which is assumed to be the plane of maximum shear stress and shear strain rate. The stress along plane AB will be dependent upon the strain, strain rate, and temperature in the primary deformation zone

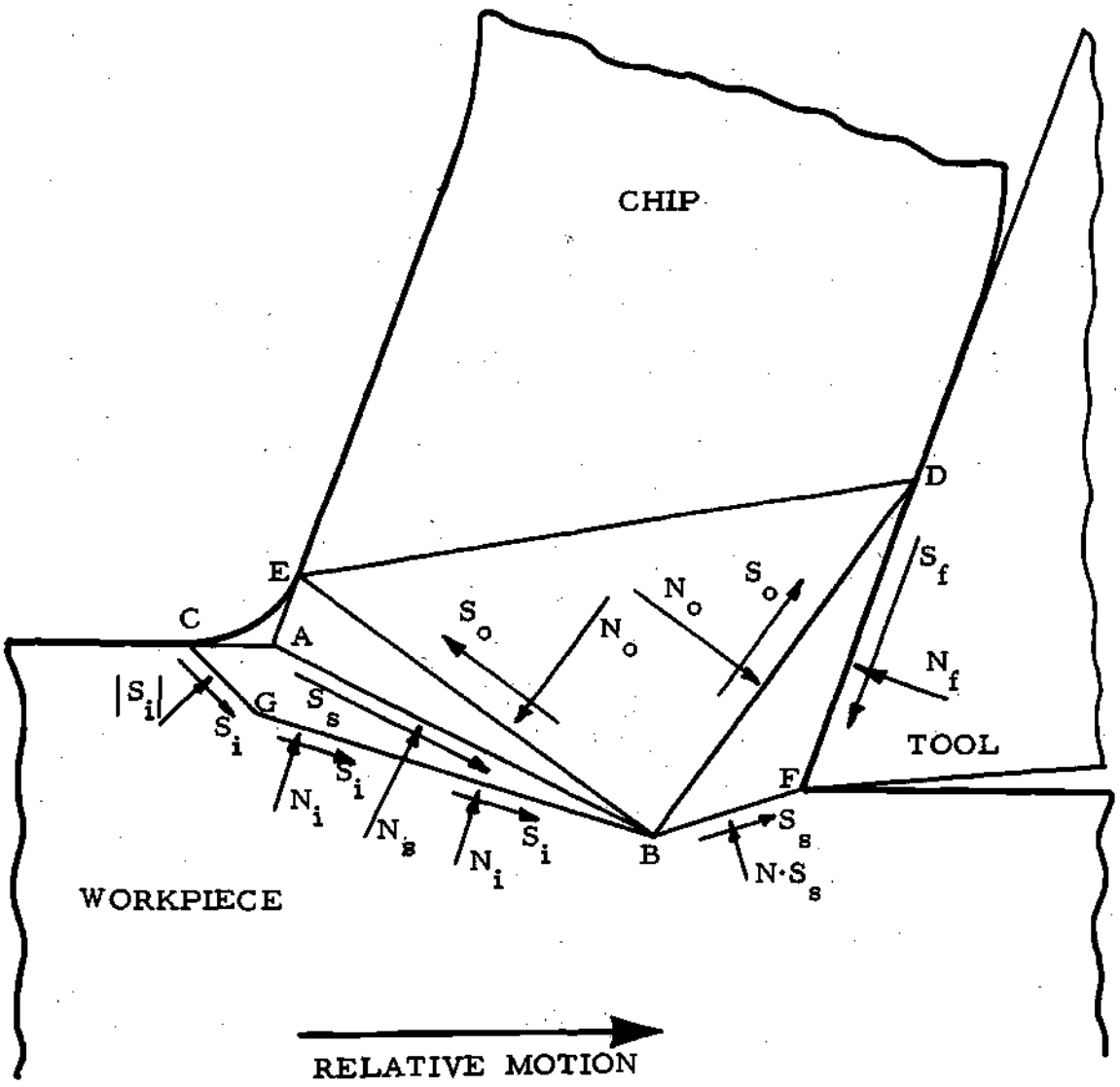


Figure 23: Model with Stresses Shown on Applicable Planes

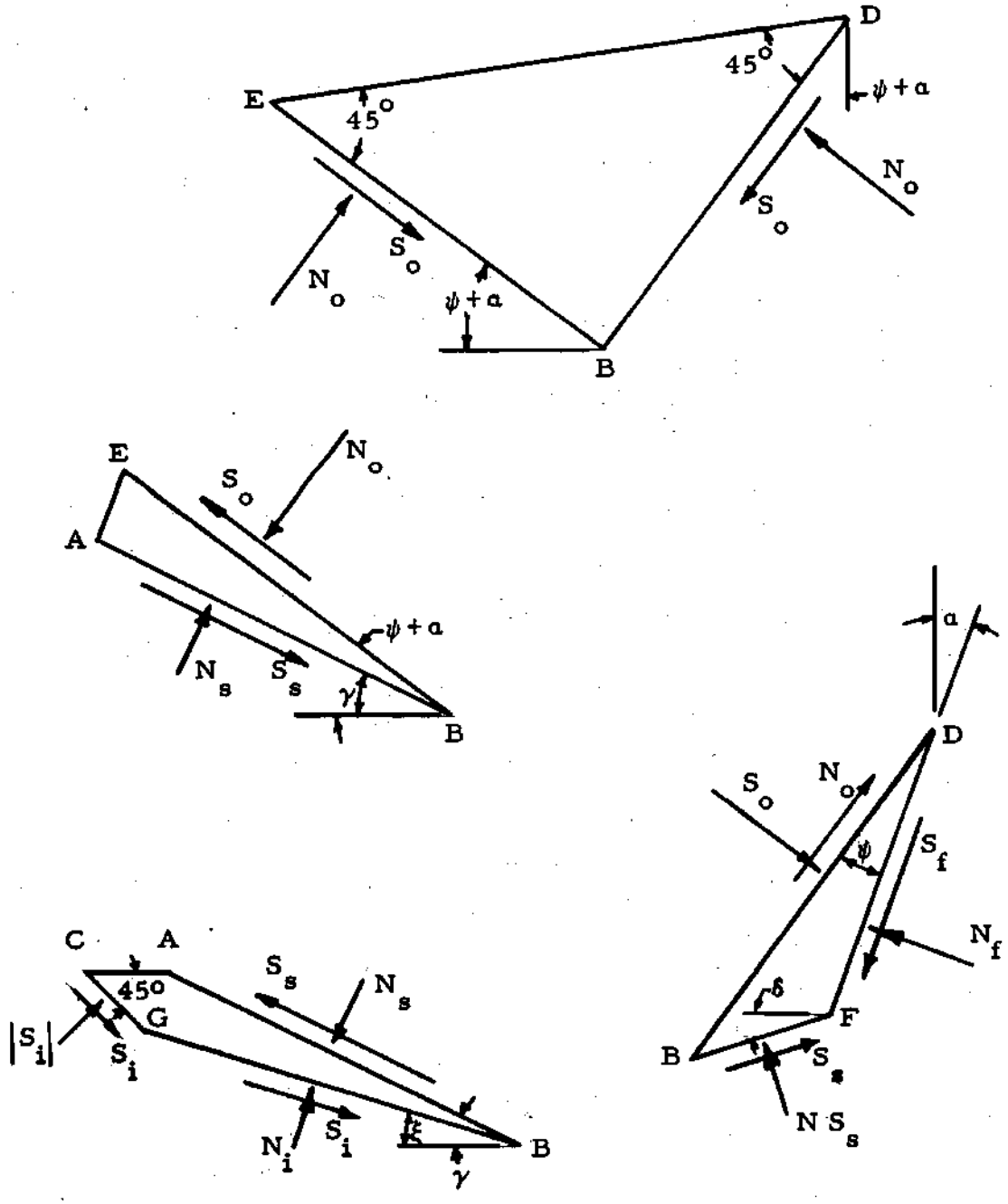


Figure 24: Individual Zones of Proposed Model

and will, therefore, vary slightly with rake angle and cutting speed. The quantitative value for S_s can be calculated from an equation of the form of Equation (24).

Once the material passes plane AB it is deformed at a rapidly decreasing strain rate until it approaches plane BE where the strain rate is very low. The plane BE approximates the upper boundary of the primary deformation zone and the shear stress on this plane (denoted by S_o) will be lower than that on plane AB due to the decreased strain rate and slight increase in temperature at normal cutting speeds, having greater effect than that of the additional plastic strain occurring between planes AB and BE.

2. Zone BDE

Stresses are transmitted from the secondary deformation zone to the primary deformation zone through the zone BDE. It is assumed that no deformation takes place in the zone but that the material is stressed to its yield point. The material passing through the secondary deformation zone will arrive at plane BD in a workhardened state, similar to that of the material at plane BE. Thus, the magnitude of the shear stress on plane BD will be very close to the magnitude of the shear stress on plane BE.

It is reasonable to assume that the forces acting on the chip after it passes through the region BDE are negligible. Hence, the shear and normal stresses on plane DE will also be negligible and no forces will be transmitted across that plane. The planes BE and BD are planes of maximum shear stress and the shear stresses on them are equal. Therefore, the triangle BDE must be a right isosoles tri-

angle with the magnitude of the normal stresses, N_o, on planes BD and BE equal to S_o in order to maintain force equilibrium.

3. Secondary Deformation Zone - BDF

All planes of the zone BDF have normal and shear stresses acting on them. It has been shown previously that the shear and normal stresses acting on plane BD are of the same magnitude, S_o. The length of plane DF is defined to be the length of the chip tool interface over which sticking occurs. The shear and normal stresses on plane DF are designated as S_f and N_f, respectively; S_f may be greater or less than the stress S_o, depending on the deformation characteristics of the material. The stress conditions on the plane DF will be shown to control directly the geometry of the cutting process.

The position of the plane BF is defined by its deflection from the horizontal and its intersection with plane BD. It will be assumed that the shear stress on plane BF is of magnitude S_s and the normal stress is of equal magnitude. The magnitude of the shear stress on plane BF will lie somewhere near S_s, because of the high strains, strain rates, and the decreased temperatures (due to heat conduction into the workpiece) present. The entire model with stresses on the appropriate planes is shown in Figure 23.

Model Analysis

The experimental model (Figures 22 and 23) can be used to develop expressions relating to the angles Ψ, δ, γ, and ξ, and the stresses S_i, S_f, N_f, S_o, S_s, and N_s to the tool forces and the cutting geometry. An additional expression is required relating the work performed in cutting

to that calculated as a function of the stresses present in the primary deformation zone.

The total energy absorbed in metal cutting is determined by the product of cutting speed and cutting force. It is composed of the work performed in the primary deformation zone and that performed in the secondary deformation zone. It is felt that it would be difficult to analyze the modes of deformation and the energy consumed on the secondary deformation zone because of the complex nature of the frictional and normal stresses and the sliding and sticking present at the chip tool interface. Hence, the "work of friction" (determined experimentally) will be subtracted from the total work in order to determine the work performed in the primary deformation zone.

The work performed in the primary deformation zone per unit time can be expressed analytically as a function of the stresses on, and deformation of an element passing through that zone. The amount of time required for this element to pass through the primary deformation zone is a function of the size of that zone. Thus, the total work performed on the element as it passes through the primary deformation zone occurs at a rate dependent upon the size of that zone. If this rate is to be consistent with the experimental results it must be equal in magnitude to the experimentally determined work rate. This constitutes an additional criterion which is applicable to the proposed model. Equations will now be derived relating the dimensionless stress ratios $\frac{S_s}{S_o}$ and $\frac{S_f}{S_o}$ and the angle parameters of the model.

Forces transmitted across planes EB and BF must be in equilibrium with the cutting and thrust forces as shown in the force polygon of

Figure 25. Resolving horizontally:

$$F_c = w\, S_o\, BE\, [\sin(\Psi+\alpha) + \cos(\Psi+\alpha)] + w\, S_s\, BF\, [\cos\,\delta - N \sin\,\delta] \quad (26)$$

and vertically

$$F_t = w\, S_o\, BE\, [\cos(\Psi+\alpha) - \sin(\Psi+\alpha)] + w\, S_s\, BF\, [\sin\,\delta + N \cos\,\delta] \quad . \quad (27)$$

Combining Equations (27) and (26) and substituting

$$\frac{BF}{BE} = \frac{\sin\,\Psi}{\cos(\alpha+\delta)} \quad , \quad (28)$$

then solving for tan δ gives

$$\tan\,\delta = \frac{Y \cos\,\alpha + \dfrac{F_t}{F_c} - N}{Y \sin\,\alpha + N\,\dfrac{F_t}{F_c} + 1} \quad , \quad (29)$$

where

$$Y = \frac{\left[\dfrac{F_t}{F_c} - 1\right] \cos(\alpha+\Psi) + \left[\dfrac{F_t}{F_c} + 1\right] \sin(\alpha+\Psi)}{\dfrac{S_s}{S_o} \sin\,\Psi} \quad . \quad (30)$$

A force polygon of triangle BDF is shown in Figure 26. Resolving parallel to the tool rake face for a unit width, w, gives

$$S_f\, DF = S_o\, BD \cos\,\Psi - N_o\, BD \sin\,\Psi + S_s\, BF\, [\sin(\alpha+\delta) + N \cos(\alpha+\delta)] \quad (31)$$

substituting

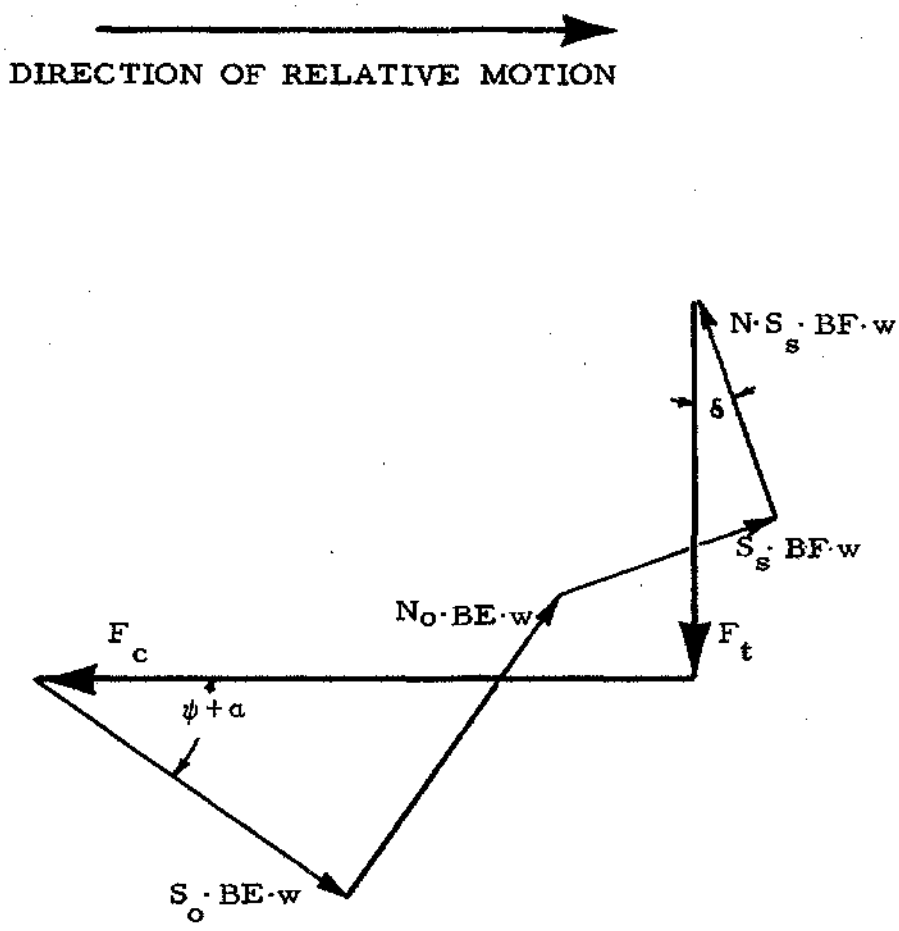


Figure 25: Force Polygon Across Surface EBF of Model

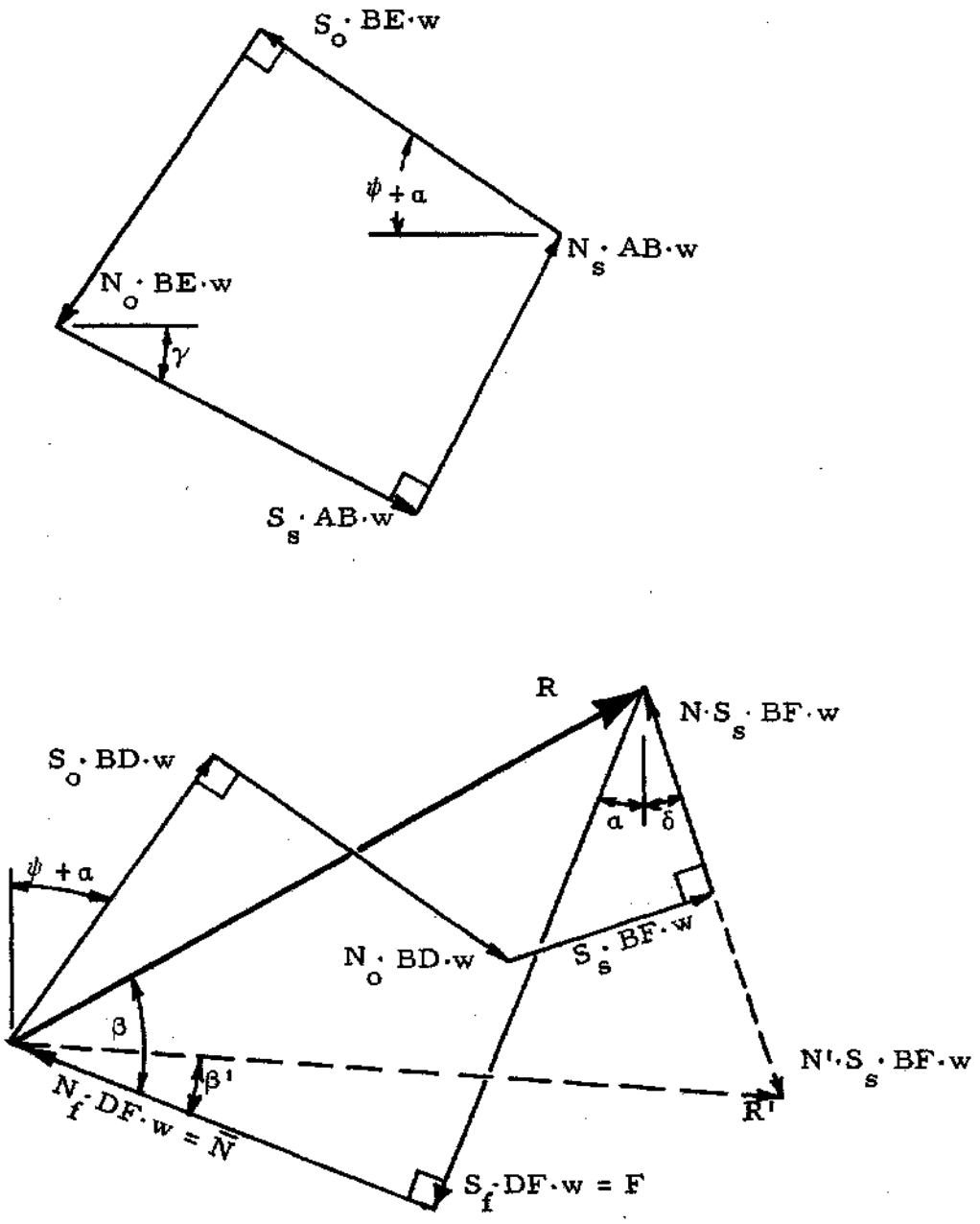


Figure 26. Force Polygons of Triangles BDF and ABE of Model

$$\frac{BD}{DF} = \frac{\cos(\alpha+\delta)}{\cos(\alpha+\delta+\Psi)} \tag{32}$$

and

$$\frac{BF}{DF} = \frac{\sin \Psi}{\cos(\alpha+\delta+\Psi)} \quad , \tag{33}$$

then simplifying, gives

$$\frac{S_f}{S_o} = \frac{1 + \tan \Psi + \frac{S_s}{S_o} \tan \Psi \left[\tan(\alpha+\delta) + N\right]}{1 - \tan \Psi \tan(\alpha+\delta)} \quad . \tag{34}$$

It can be shown from Figure 22 that the undeformed chip thickness, t_1, is given by

$$t_1 = AB \sin \gamma - BF \sin \delta \tag{35}$$

and the chip thickness, t_2, by

$$t_2 = BE \cos \Psi + BD \sin \Psi \quad . \tag{36}$$

Substituting

$$BE = BD \quad , \tag{37}$$

$$\frac{AB}{BE} = \frac{\cos \Psi}{\cos(\gamma-\alpha)} \quad , \tag{38}$$

and

$$\frac{BF}{BD} = \frac{\sin \Psi}{\cos(\alpha+\delta)} \quad , \tag{39}$$

and then solving for the cutting ratio, r_c, where r_c is defined by Equation (5), gives:

$$r_c = \frac{\cos \Psi \sin \gamma}{\cos(\gamma-\alpha)\,[\cos \Psi + \sin \Psi]} - \frac{\sin \Psi \sin \delta}{\cos(\alpha+\delta)\,[\cos \Psi + \sin \Psi]} \quad . \tag{40}$$

Rearranging Equation (40) gives

$$\tan \gamma = \frac{\Gamma \cos \alpha}{\left[\frac{1}{(1+\tan\Psi)}\right] - \Gamma \sin \alpha} \quad , \tag{41}$$

where

$$\Gamma = r_c + \frac{\tan \Psi \sin \delta}{\cos(\alpha+\delta)\,[1 + \tan \Psi]} \quad , \tag{42}$$

The force polygon for the triangle ABE is shown in Figure 27. Resolving parallel to AB

$$S_s\, AB\, w = w\, BE\, S_o \{ \cos[\Psi-(\gamma-\alpha)] + \sin[\Psi-(\gamma-\alpha)] \} \quad . \tag{43}$$

Substituting

$$\frac{EB}{AB} = \frac{\cos(\gamma-\alpha)}{\cos \Psi} \tag{44}$$

gives

$$\frac{S_s}{S_o} = \{[1 + \tan \Psi] \cos(\gamma-\alpha) - [1 - \tan \Psi] \sin(\gamma-\alpha)\} \cos(\gamma-\alpha) \quad . \tag{45}$$

The lengths of the planes of the proposed model can also be determined using the fact that BE and BD are of equal length. Rearranging Equation

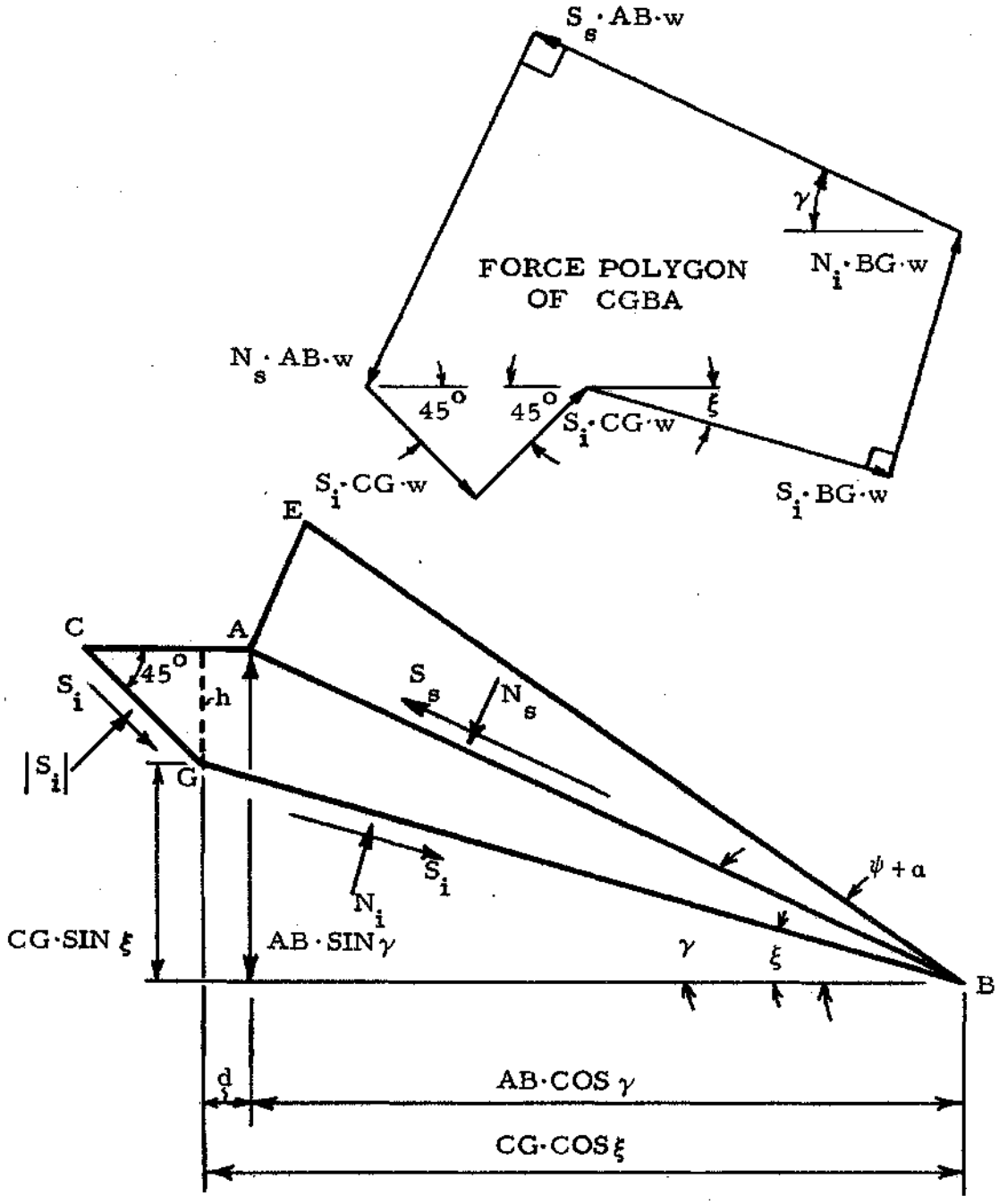


Figure 27. Primary Deformation Zone of Model

(36) gives:

$$BE = \frac{t_2}{(\cos \Psi + \sin \Psi)} \tag{46}$$

from triangle BDF:

$$BF = \frac{BD \sin \Psi}{\cos(\alpha+\delta)} \tag{47}$$

and

$$DF = \frac{BD \cos(\alpha+\Psi+\delta)}{\cos(\alpha+\delta)} \quad , \tag{48}$$

and from triangle ABE:

$$AB = \frac{BE \cos \Psi}{\cos(\gamma-\alpha)} \quad . \tag{49}$$

Rearranging Equation (26) gives:

$$S_o = \frac{F_c}{w \left\{ BE \left[\sin(\Psi+\alpha) + \cos(\Psi+\alpha)\right] + \frac{S_s}{S_o} BF \left[\cos \delta - N \sin \delta\right] \right\}} \quad . \tag{50}$$

An equilibrium diagram of the forces acting on tetrahedron CGBA is shown in Figure 27. Solving for the initial shear strength of the workpiece material, S_i, gives:

$$S_i = \frac{S_s \cos(\gamma-\xi) + N_s \sin(\gamma-\xi)}{1 + 2 \cos \xi \left[\sin \gamma - \sin \xi\right]} \quad , \tag{51}$$

where the normal stress on plane AB (N_s) is obtained by resolving forces

acting on triangle ABE perpendicular to plane AB; that is,

$$N_s = S_o \frac{BE}{AB} [\cos(\Psi+\alpha-\gamma) - \sin(\Psi+\alpha-\gamma)] \quad , \tag{52}$$

and where the shear stress S_s is written as:

$$S_s = \left\{ \frac{S_s}{S_o} \right\} S_o \quad . \tag{53}$$

The angle ξ can be determined from Equation (51) for a given initial shear strength of the workpiece material, S_i, where $(0 < \xi < \gamma)$.

In order to compute the work performed in the primary deformation zone a value for the mean stress on that zone is required. The actual stress will be somewhat greater than S_i and less than S_s. (Preliminary computations showed that the stress was close to S_o over a wide range of cutting conditions and therefore this value was used in all subsequent calculations.)

The sum total of all work per unit time performed in the primary deformation zone in compression and shear is given by (see Appendix II):

$$W_{pt} = S_o w \left[\frac{1 - r_c^2}{2 r_c} + \tan \nu \right] \frac{A_{pdz}}{T_{rq}} \quad , \tag{54}$$

where the average time required for an element to pass through this zone is given approximately by (see Appendix II):

$$T_{rq} = \frac{AB\ (\Psi+\alpha-\xi)}{V_c(1+r_c)} \quad , \tag{55}$$

and where the area of primary deformation zone is approximately

$$A_{pdz} = \frac{1}{2} \{AB\}^2 (\Psi+\alpha-\xi) + \frac{1}{2} h\ AC \quad . \tag{56}$$

The angle $(\Psi+\alpha-\xi)$ is expressed in radians, and the length of plane AC is given by:

$$AC = AB\ [\sin \gamma - \sin \xi + \cos \xi - \cos \gamma] \quad . \tag{57}$$

The perpendicular distance, h, from point G to plane AC (Figure 27) is

$$h = AB\ [\sin \gamma - \sin \xi] \quad . \tag{58}$$

The angle ν is the angle through which a unit square element must be sheared to maintain continuity of material flow throughout deformation and is given by (see Appendix II):

$$\tan \nu = \frac{r_c \cos \phi - \sin(\alpha-\phi)}{\cos(\alpha-\phi)} \quad . \tag{59}$$

The total work rate performed during the cutting operation is given by:

$$W_{tl} = F_c\ V_c \quad . \tag{1}$$

The work rate performed by "friction" is given by:

$$W_{kf} = F\ V_c\ r_c \quad , \tag{60}$$

where the force parallel to the rake face of the tool is given by:

$$F = F_c \sin \alpha + F_t \cos \alpha \quad . \tag{61}$$

The work rate performed in the primary deformation zone (as determined experimentally) is then given by:

$$W_{pd} = W_{tl} - W_{kf} \quad . \tag{62}$$

Sufficient expressions have now been derived to analyze cutting test data. The analysis is performed in the following manner.

The basic material properties of mass density (ρ), specific heat (C_p), and thermal conductivity (k), are obtained from standard tables. The initial shear strength of the work material (S_i) is determined by a comparison of the initial microhardness of the workpiece and that listed in a materials handbook. A cutting test is performed with a fixed cutting speed (V_c), rake angle (α), chip width (w), and undeformed chip thickness (t_1). The results of the cutting test yield the chip thickness (t_2) the cutting force (F_c), and the thrust force (F_t).

Using an iterative procedure the angle Ψ is found which results in agreement between W_{pt} and W_{pd} with the desired degree of accuracy while maintaining the equality of the system of Equations (28) to (51) for the angles δ, γ, ξ, S_i, and the stress S_f. Although multiple solutions may exist for the angle Ψ, from the geometry one can observe that the range of interest will be such that

$$0 < \Psi < \frac{\pi}{2} \quad ,$$

and that Ψ will generally be small. The trivial case of no secondary

deformation zone existing occurs when Ψ is equal to 0. This solution completely defines the geometry of the model and the dimensionless stress ratios $\frac{S_s}{S_o}$ and $\frac{S_f}{S_o}$ for a given set of cutting conditions.

CHAPTER V

MODEL APPLICATION

The preceding chapter has shown how the proposed model can be used in the analysis of experimental results, given α, V_c, t_1, t_2, F_c, F_t for a particular metal cutting test. In order to test the complete validity of the model it must be capable of analyzing experimental data produced from a wide range of cutting conditions. The range of experimental cutting tests analyzed with the present model was limited at low cutting speeds and low rake angles by the formation of a built-up edge on the tool rake face and at high speeds by exceeding the power available to perform the cutting operation. The geometry of the dynamometer precluded using rake angles greater than 45 degrees.

The numerical values for the stresses S_s, S_o, and S_f, the angles δ, γ, ξ, and Ψ, and the stress ratio $\frac{S_s}{S_o}$ for each test were determined by selecting the angle Ψ which gave agreement between the work performed in the primary deformation zone as determined by the experimentally measured tool forces and that determined from the stresses and the assumed mode of deformation in the primary deformation zone. These stress values are listed in Tables 3, 4, 5, and 6 in Appendix I. It is seen that the only stress which remains approximately constant is S_s, and a means of correlating the other stresses with the individual tests is required. Further analysis of the machining process must be made.

The stress required to deform any workhardened material depends

on its previous strain history, temperature, and the rate at which deformation is occurring. Hence, these quantities should be included in any analysis of the metal cutting process. In order to explain satisfactorily changes in S_f, S_o, S_s, and $\frac{S_s}{S_o}$, it is necessary to examine the strain, strain rate, and temperature conditions in both the primary and secondary deformation zones.

The shear strain associated with machining for a shear plane model of the cutting process (the use of this plane being justifiable because in this area the mode of deformation is not important) is given by:

$$\gamma_s = \cot \phi + \tan(\phi-\alpha) \tag{63}$$

after Merchant[1,2], where ϕ is the shear angle as defined by Equation (4).

The average rate of strain in the primary deformation zone which depends on the average size of that zone is given by (see Appendix II):

$$\dot{\gamma}_1 = 0.2\ \gamma_s\ V_c\ [1 + r_c]/[AB(\Psi+\alpha-\xi)]\ \sec^{-1} \quad . \tag{64}$$

If a parabolic velocity distribution throughout the secondary deformation zone is assumed as being reasonable (see reference 15) then the strain rate is given by:

$$\dot{\gamma}_2 = \frac{0.4\ V_c\ r_c}{l_o \tan \Psi}\ \sec^{-1} \quad , \tag{65}$$

where l_o is the chip tool length, i.e., plane DF of Figure 22.

Procedures for calculating the temperature in the primary and secondary deformation zones based on plane heat sources and a shear

plane model of the metal cutting process have been given by several workers[45,49]. These procedures have been shown to give results in good agreement with experimental data[48] and it is proposed to use them in the present work. Consequently, a mean or average temperature will be computed for the zones rather than the complete temperature distribution as it actually occurs.

The total amount of heat generated during the cutting process is given by

$$q_{tl} = \frac{F_c V_c}{1400} \quad \frac{CHU}{min} \quad . \tag{66}$$

The amount of heat generated by forces parallel to the rake face of the tool is given by

$$q_f = \frac{F V_c r_c}{1400} \quad \frac{CHU}{min} \quad , \tag{67}$$

where F is defined by Equation (61). The heat generated in the primary deformation zone due to deformation is approximately the difference of Equations (66) and (67), that is,

$$q_s = q_{tl} - q_f \quad \frac{CHU}{min} \quad . \tag{68}$$

The percentage of this heat which is conducted into the workpiece is given by

$$\beta_s = 0.475 - 0.1498 \ln \theta \quad , \tag{69}$$

or

$$\beta_s = 0.10, \quad \text{if } \theta > 12 \quad , \tag{70}$$

after Weiner[45], where θ is the thermal number and is given by

$$\theta = 720 \left[\frac{\rho\ c_p}{k}\right] V_c\ t_1\ \tan \phi \quad . \tag{71}$$

The maximum possible uniform temperature rise of the chip due to the deformation in the primary deformation zone is given by

$$\theta_{ts} = \frac{q_s}{[12\ \rho\ c_p\ V_c\ t_1\ w]} \quad {}^{o}C \quad . \tag{72}$$

Consideration of the heat transmitted to the workpiece gives an approximation to the average uniform temperature rise of the chip due to shear deformation in the primary deformation zone. This temperature rise is clearly

$$\theta_s = [1 - \beta_s]\ \theta_{ts} \quad {}^{o}C \quad . \tag{73}$$

The average temperature rise of the chip due to "friction" at the chip tool interface is given by

$$\theta_f = \frac{q_f}{[12\ \rho\ c_p\ V_c\ t_1\ w]} \quad {}^{o}C \quad , \tag{74}$$

and the maximum temperature rise at the chip tool interface by

$$\theta_{mx} = 0.72\ B \left[\left[0.856\right]^{-[0.4\ B \left[\frac{l_o}{t_2}\right]\ \tan \Psi]}\right] \theta_f \quad {}^{o}C \quad , \tag{75}$$

after Boothroyd[48,50] where:

$$B = \left[\frac{720 \left[\frac{\rho \, c_p}{k} \right] V_c \, t_1}{\left[\frac{l_o}{t_1} \right]} \right]^{\frac{1}{2}} , \qquad (76)$$

and l_o is the chip tool contact length (plane DF of the present model). The maximum temperature rise of the chip at the chip tool interface is thus

$$\theta_{ma} = \theta_{mx} + \theta_s \quad {}^{o}C \quad . \qquad (77)$$

It is clear at this stage that equations relating the stress to the strain, strain rate, and temperature in the primary and secondary deformation zones are required, i.e., the functional relationship:

$$\tau_i = f_i(\gamma_s, \dot{\gamma}_i, T_i) \qquad (78)$$

must be evaluated. In the present work it was decided to use an expression of the form

$$\tau_i = \sigma_o \, G^T \, \gamma_s^{(A+BT)} \, \dot{\gamma}_i^{(C+DT+F[\ln\gamma_s]T)} , \qquad (79)$$

where i is 1, 2, or 3 and refers to one of the stresses S_s, S_o, or S_f; γ_s is the shear strain; $\dot{\gamma}_i$ is the shear strain rate; T is temperature in ^{o}C; and σ_o, G, A, B, C, D, and F are constants. The constant C permits the use of an arbitrary point of reference for the temperature T. In this work the reference point was taken as the ambient temperature.

Equation (79) was used as it is slightly more general than that proposed by Lubahn[21], and it gave slightly better results.

The results of cutting tests over a wide range of experimental conditions were substituted into Equation (79) and the constants of the functional relationships between the stresses, strains, strain rates, and temperatures determined. These equations were then used to predict S_f, S_o, and $\frac{S_s}{S_o}$. The percentage error of the prediction of the quantities S_f and $\frac{S_s}{S_o}$ are shown in Tables 5 and 6 in Appendix I. Errors in predicting S_s are of the order of one percent. It can be seen from Tables 5 and 6 that the percentage error for all predictions are extremely small, thus giving strong justifications of the validity of the present model.

CHAPTER VI

MODEL UTILIZATION

Introduction

The present model of the orthogonal metal cutting process differs from most others previously developed in that it can be used to predict qualitatively the effects of changes in cutting speed and rake angle on the tool forces and the geometry of the cutting process. The purpose of this chapter is to develop the functional relationships which make such predictions possible.

The functional relationships developed have been solved by a complex iterative computer procedure (see Appendix III). The results of this solution are compared with the experimental results in Figures 29 through 37 in Appendix I for the complete range of cutting speeds and rake angles used in the experimental investigation.

The multivalue characteristics of trigonometrical functions can lead in some cases to unrealistic solutions of an equation. The solutions of some trigonometric equations were obtained by an iterative procedure within a selected range of the angular variables which would give a realistic geometry. For example, it would seem intuitively obvious that the angle Ψ would lie in the range of $0 < \Psi < (90-\alpha)$. Similar deductions can be made with respect to other angles (i.e., $0 < \gamma < (\Psi+\alpha)$, $0 < \xi < \gamma$, etc.).

The known input parameters are the undeformed chip thickness (t_1),

the cutting speed (V_c), the rake angle (α), the material properties (ρ, C_p, k, S_i), and the constants for the stress, strain, strain rate, and temperature equation (Equation (79)) describing the stresses S_o, S_f, and S_s. These constants were determined from metal cutting tests since data concerning the properties of materials under the conditions of strain, strain rate, and temperature present during metal cutting are not currently available.

Given the seven input conditions, a solution to the problem of determining a unique geometry and the cutting forces may exist if the number of unknown dependent variables and associated equations does not exceed the numbers of known independent variables. The unknown variables are the angles Ψ, δ, γ, and ξ, the cutting and thrust forces (F_c and F_t) and the chip thickness (t_2). Thus, it is at least possible for a solution to exist.

Utilization

The block diagram for the iterative procedure used is shown in Figure 28. The stress values for S_s and S_o lie within a relatively small range. Any initial estimate of their values will be only a relatively small amount in error. In order to begin the iterative process initial values of S_s and S_o are assumed. Trial values of the angles Ψ and δ are also assumed. The angle γ is found by satisfying the previously derived relationship:

$$\frac{S_s}{S_o} = \{[1 + \tan \Psi] \cos(\gamma-\alpha) - [1 - \tan \Psi] \sin(\gamma-\alpha)\} \cos(\gamma-\alpha) \qquad (45)$$

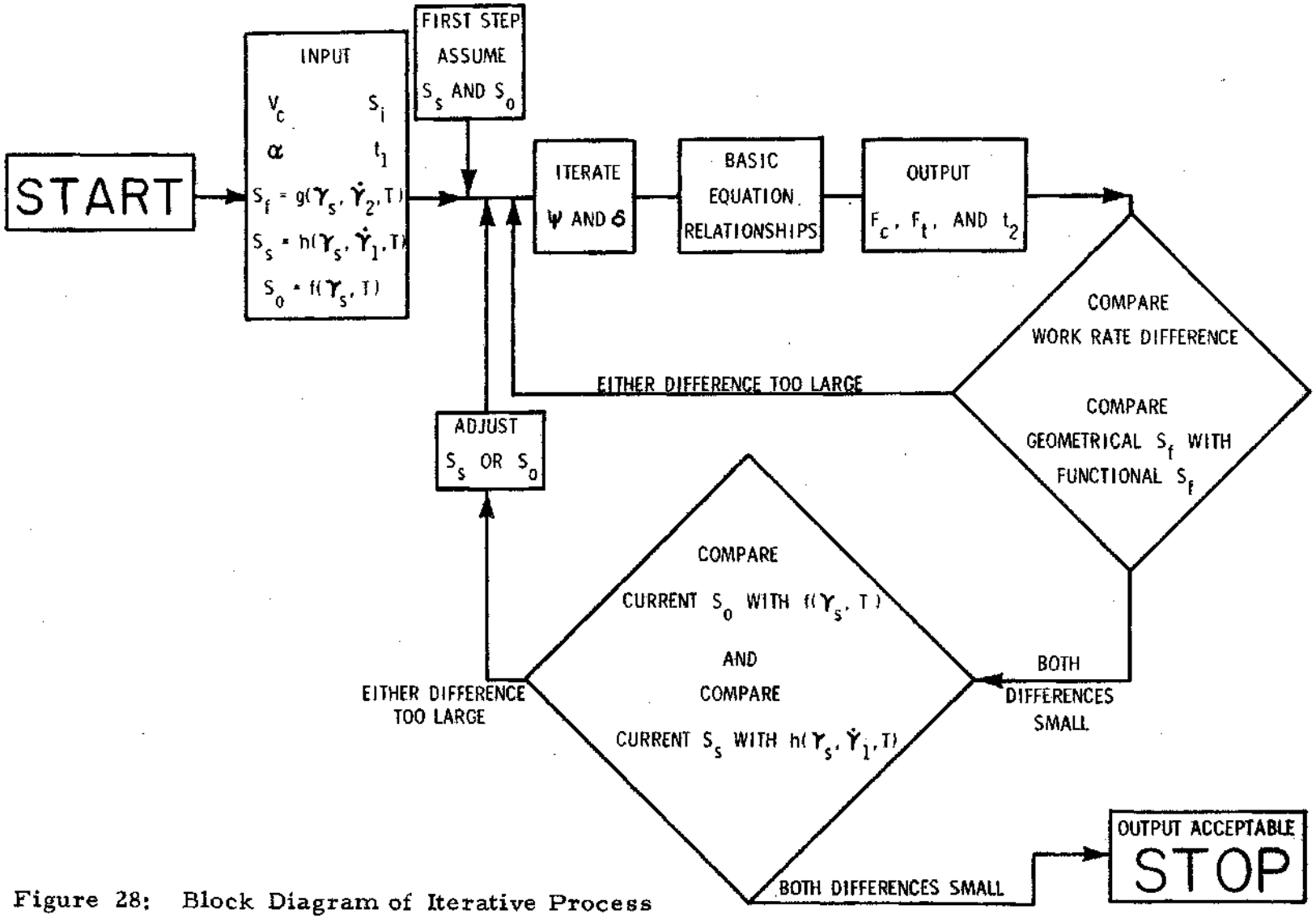


Figure 28: Block Diagram of Iterative Process

in the range $0 < \gamma < (\Psi+\alpha)$.

The cutting ratio r_c is then calculated from the expression:

$$r_c = \frac{\cos \Psi \sin \gamma}{\cos(\gamma-\alpha)\,[\cos \Psi + \sin \Psi]} - \frac{\sin \Psi \sin \delta}{\cos(\alpha+\delta)\,[\cos \Psi + \sin \Psi]} \quad , \tag{40}$$

and the chip thickness from

$$t_2 = \frac{t_1}{r_c} \quad . \tag{80}$$

The cutting and thrust forces are obtained from

$$F_c = w\, S_o\, BE\, [\sin(\Psi+\alpha) + \cos(\Psi+\alpha)] + w\, S_s\, BF\, [\cos \delta - N \sin \delta] \tag{26}$$

and

$$F_t = w\, S_o\, BE\, [\cos(\Psi+\alpha) - \sin(\Psi+\alpha)] + w\, S_s\, BF\, [\sin \delta + N \cos \delta] \tag{27}$$

where

$$BE = \frac{t_2}{[\cos \Psi + \sin \Psi]} \tag{81}$$

and

$$BF = \frac{BD \sin \Psi}{\cos(\alpha+\delta)} \quad . \tag{47}$$

In order to maintain force equilibrium the stress S_f must satisfy the expression:

$$S_f = S_o \left[\frac{S_f}{S_o}\right] \quad , \tag{82}$$

where $\left[\frac{S_f}{S_o}\right]$ is determined from Equation (34), and S_f, as a function of the strain, strain rate, and temperature (determined through Equation (63) to Equation (77)) of the secondary deformation zone, is calculated from Equation (79). A comparison of the two means of calculating the rate of work performed in the primary deformation zone (Equations (54) and (62)) is made. A satisfactory trial solution is found when this comparison and Equation (82) are both simultaneously satisfied.

The previously assumed values of the stresses S_s and S_o are now compared with those predicted through use of the general stress equation, Equation (78), or the specific one, Equation (79). If there is a significant difference, new values for S_s, S_o, Ψ, and δ are taken and the procedure is repeated until all differences are sufficiently small.

The results of applying this process over the range of rake angles from 20 to 45 degrees and speeds of 80 to 480 surface feet per minute are plotted in Figures 29 through 37 in Appendix I. A discussion of the results and the assumptions necessary for the analysis follows in Chapter VII.

CHAPTER VII

DISCUSSION

Figure 29 is a plot of the shear angle (ϕ) versus the difference between the friction angle (β) and rake angle (α). Many of the shear angle theories[1,2,5,7,8, etc.] and the experimental work upon which these workers base their statements indicate that this graph should be a straight line. It can be seen from Figure 29 that it could be possible to place a "best" straight line through the least means square average of the experimental data points with only a small amount of deviation. Furthermore, this straight line would be relatively close to another passed through the least means square average of the predicted data points. Thus, by the current standards of metal cutting analysis the model developed here is of acceptable quality.

The value of the model cannot be judged from an all-inclusive plot such as Figure 29. A more realistic judgment of the value of the model can be made through evaluation of Figures 30, 31, 32, and 33, in which the trends of the predicted friction angle and the predicted shear angle agree extremely well with the results of experimental cutting tests for both the variation resulting from changes in rake angle and the variation resulting from changes in cutting speed. Thus, a qualitative prediction of the effects of changing the cutting speed of orthogonal machining of aluminum has been made with extremely good accuracy.

The results of using the developed model to predict the effects

of the change of speed and rake angle on the chip thickness, Figures 34 and 35, and the cutting forces, Figures 36a, 36b, and 37a, 37b, are also excellent. It is extremely doubtful that a better approximation to the experimental data points shown for the two angle parameters or that a much better one for the forces of cutting and the chip geometry could be obtained over the entire range of speeds and rake angles. This qualitative agreement is the most significant indication of the value of the model developed.

The primary result of this research is the model of the metal cutting process and as such the assumptions used in its development are of prime importance. Overall justification of the sum total of all assumptions made can be effectively summarized in the fact that the model accurately predicts the effects of changes in cutting speed on the chip thickness and the forces of cutting. Specific justification of the individual assumptions will now be made.

Basic Assumptions

Justification of the basic assumptions of the metal cutting process is not exceptionally difficult. The analysis of non-plane strain conditions would be exceedingly and unnecessarily complex and would add a third dimension to the force, displacement, stress, and strain vectors obtained. The presence of a built-up edge at the chip-tool interface would most probably lead to non-steady state conditions during cutting. This would exceed the applicability of any model to be developed at this time.

A single phase material whose deformation characteristics can be

described by a single equation is theoretically possible; however, to date the development of that equation independently has not occurred in the range of high strains, strain rates, and temperatures inherent in the metal cutting process. This difficulty was overcome by the use of metal cutting tests to determine an applicable material property equation. In doing this if errors are introduced in using the experimental metal cutting tests to develop the constitutive equations for each stress, they preclude the use of that constitutive equation for any purpose other than the analysis of other metal cutting data. As such, the errors made in developing a constitutive equation will be self cancelling when that equation is used to show the functional relationship between stress, strain rate, and temperature for the appropriate material when deformed in a metal cutting test.

The use of a lubricant during the cutting process is precluded due to its indeterminate cooling properties and the questionable capability of generating an appropriate expression for the shear stress at the chip-tool interface.

A standard metal cutting analysis using the shear plane approach for determination of many metal cutting characteristics was necessary in order to satisfactorily complete the analysis. A new derivation for determining the strain, percentage of heat conducted to the workpiece, and temperature rise at the chip-tool interface would be beyond the scope of this analysis and would not add appreciably to the analysis.

Model Geometry Assumptions

Primary Deformation Zone

The assumption that the initial shear strength of the work material can be represented as a constant shear stress along surface CGB is justifiable as being a mechanical property of the workpiece material. In order to maintain static equilibrium a surface does exist along which a shear stress of constant magnitude acts. Plasticity theory indicates that a surface of maximum shear stress intersects a free surface at 45 degrees and will have shear and normal stresses of equal magnitude acting thereon. Plane CG is defined as having the properties of being a plane of maximum shear stress and it intersects a free surface. Although it is not defined as being a slip line, the analogy is made that plane CG does intersect the free surface at 45 degrees and does have equal shear and normal stresses acting on it.

The assumption that plane BG and plane AB are of equal length is purely arbitrary. However, it is readily apparent that a small variation in the length of plane BG would result in only a slight variation in the quantitative results of analyzing an experimental cutting test (those quantitative results being the numerical values of the angles Ψ and δ). Preliminary computations showed that a consistent variation of 10 percent in the length of plane BG had very little effect on the results of analyzing and predicting the results of a series of metal cutting tests.

The plane AB is assumed to be the plane of maximum shear stress. A free body diagram of the Primary Deformation Zone with stresses acting on the appropriate planes will indicate that plane AB is the shortest

plane which will intersect the free surface CAE and pass through point B. Hence, in order to maintain static equilibrium the stress on plane AB will be a maximum.

Secondary Deformation Zone

The shear stress on plane BD is assumed to be equal to that on plane BE. This assumption is reasonable in light of the fact that the material along plane BD will have been deformed to a large amount of strain, as will the material along plane BE. The material along plane BD will most probably have been strained slightly more than that along plane BE but it is most probably at a slightly higher temperature. Hence, these two factors will tend to offset each other and the assumption of equal stresses being present is not unreasonable. A plane will exist which intersects the free surface near the tool flank in a manner similar to the plane CG. This plane will be physically close to plane DF and will have equal shear and normal stresses acting on it. The magnitude of the stresses acting on plane DF is assumed to be equal to S_s because of the high strain to which the material has been subjected as it passed through the primary deformation zone and the cooling effects of the work-piece material. An intuitive case can be made to justify the direction of the normal stress on plane BF as being either tensile or compressive. However, in order to maintain static equilibrium of a reasonably shaped zone BDF with S_f being larger than N_f, it is apparent that the normal stress along plane BF must be compressive. A qualitative justification of this is shown in Figure 26 where, if a reasonable geometry of the cutting process is assumed, i.e., the angles Ψ and δ are relatively small, the friction angle β would be of the magnitude shown as β' in Figure 26.

In most metal machining, the friction angle is much larger than this decreased angle, β'.

The tool nose forces have been neglected because their relative magnitude is small, while the static equilibrium of the chip requires that the tool nose forces be transmitted across surface CGBF and hence at least a large portion of the tool nose forces are inherent in the analysis of experimental data.

The determination of the strain rate of the secondary deformation zone is based on the assumption that the velocity distribution therein is parabolic. This may be in error but the error will be systematic throughout the analysis and hence will be self-cancelling in predicting metal cutting test results. A similar justification can be made for the development of the average strain rate in the primary deformation zone. This is acceptable in the present analysis because the comparison is qualitative.

Thus, individual basic assumptions inherent to this analysis are, at least in part, justifiable and the sum total of all errors associated with the assumptions do not result in large variation in the ability of the model to predict metal cutting results.

Independent Correlation

Zorev[46] found an area of sticking and an area of sliding between the chip and tool at the chip-tool interface. This has been verified analytically by Bailey and Boothroyd[15]. These works form the basis for neglecting the sliding region at the chip-tool interface in the present work.

In high speed hot machining of chromium-molybdenum steels, Sata[40] found the shear stress in the shear zone remained approximately constant with increased cutting speed but decreased with rising temperature of the workpiece. This is especially significant since an increase in speed yielded large increases in cutting temperature. The conclusion drawn by Sata was that the effects of an increase in strain rate were offset by the effects of an increased cutting temperature. Ostafiev and Kobayashi[32] found that the stress-strain curve obtained during metal cutting yielded a slightly higher stress for a given strain than that of a static compression test. The results of these two experimental investigations support the use of an equation of the form of Equation (79) to describe the deformation characteristics of a generalized material during metal cutting.

Shaw[23] has listed the important factors in the orthogonal metal cutting process in an approximate order of importance as follows.

"1. Chips are produced by a shear process.

2. There is a strong interaction between the shear deformation occurring in the shear zone and that occurring on the tool face.

3. Most materials strain harden.

4. A built-up edge is usually present at low cutting speeds.

5. At high cutting speeds a secondary shear zone is present in the chip along the tool face.

6. Chips frequently curl and this in turn changes the chip-tool contact length.

7. The chip-tool contact length may be controlled by tool design.

8. Dull tools or tools cutting with a large BUE will have a rounded cutting edge." (BUE is an acronym for built-up edge.)

"9. Forces exist on the relief face of a tool, especially when an appreciable wear land is present.

In addition to the steady-state problem there are several important problems associated with non-steady state input conditions, such as variable undeformed chip thickness (t), speed (V), rake angle (α), depth of cut (b), or material properties. . . . Solutions that incorporate the important concepts of items 2, 4, and 5 seem to be missing."

The model as developed in the present work has included many of these phenomena noted by Shaw[23]. Of the five more important phenomena, only the built-up edge is excluded from this analysis. Variations of chip geometry and cutting forces with variable cutting speed are included.

CHAPTER VIII

CONCLUSIONS

The results of the development of a theoretical model of orthogonal machining are quite good in that (a) the change of chip geometry and cutting forces resulting from changes in rake angle are qualitatively predicted extremely well, and (b) the changes of chip geometry and cutting forces resulting from changes in cutting speed are also qualitatively predicted extremely well.

The model proposed in the present work is a significant advancement in the understanding of the orthogonal machining process.

CHAPTER IX

RECOMMENDATIONS

It is felt that further development of this work would be redundant with the exception of further study of the built-up edge. It is not felt that the extension of the present work to a built-up edge analysis would be feasible.

In order to prove the generality of the analysis, application of the model to other materials could be made in the future.

A great deal of work is required in order to understand the behavior of materials at high deformation rates and varying temperatures. Until advancements occur in this field further metal cutting analyses will be of limited value.

APPENDIX I

EXPERIMENTAL RESULTS

Table 1. Nominal and Actual Cutting Speeds and Rake Angles

Nominal Rake Angle (degrees)	Actual Rake Angle (degrees)	Nominal Cutting Speed (SFPM)	Actual Cutting Speed (SFPM)
20	18.5	80	78
25	25.3	120	117
30	29.6	160	156
35	34.3	240	235
40	40.0	320	310
45	45.0	480	470

Table 2. Experimental Cutting Test Results

Rake Angle (degrees)	Cutting Speed (SFPM)	Cutting Force (pounds)	Thrust Force (pounds)	Chip Thickness (inches)
20*	80	726.4	400.1	0.116
25	80	684.6	339.2	0.110
30	80	634.5	269.6	0.098
35	80	542.7	200.0	0.085
40	80	450.8	147.8	0.066
45	80	400.7	113.0	0.053
20*	120	684.6	382.7	0.110
25	120	642.9	313.1	0.102
30	120	584.4	243.5	0.091
35	120	500.9	182.6	0.078
40	120	425.8	139.1	0.063
45	120	384.0	104.3	0.052
20*	160	642.9	356.6	0.105
25	160	601.1	295.7	0.096
30	160	551.0	226.1	0.084
35	160	467.5	165.2	0.072
40	160	409.1	113.0	0.060
45	160	375.7	95.6	0.051
20*	240	617.8	313.1	0.101
25	240	576.1	260.9	0.091
30	240	526.0	208.7	0.079
35	240	450.8	147.8	0.067
40	240	400.7	104.3	0.057
45	240	367.3	86.9	0.050
20*	320	592.8	287.0	0.096
25	320	551.0	234.8	0.085
30	320	492.6	191.3	0.073
35	320	434.1	130.4	0.063
40	320	392.4	95.6	0.054
45	320	359.0	86.9	0.048
30	480	450.8	173.9	0.069
35	480	417.4	121.7	0.061
40	480	384.0	86.9	0.052
45	480	350.6	78.2	0.046

* Data questionable due to built-up edge possibility.

Table 3. Stress $S_s \times 10^{-3}$ in psi

Cutting Speed (SFPM)	Rake Angle (degrees)					
	20*	25	30	35	40	45
80	22.0	21.6	21.9	20.9	21.3	22.5
120	21.6	21.6	21.4	20.7	20.8	21.8
240	20.6	20.9	21.4	20.8	21.1	21.5
320	20.5	21.1	21.3	21.1	21.6	21.5
480	**	**	20.3	20.8	21.9	22.0

* Data questionable due to built-up edge possibility.

** Exceeded power of lathe.

Table 4. Stress Ratio $\frac{S_s}{S_o}$

Cutting Speed (SFPM)	Rake Angle (degrees)					
	20*	25	30	35	40	45
80	1.467	1.462	1.422	1.361	1.284	1.229
120	1.434	1.411	1.369	1.310	1.251	1.209
160	1.396	1.363	1.323	1.263	1.225	1.197
240	1.336	1.323	1.285	1.228	1.202	1.184
320	1.332	1.300	1.250	1.212	1.190	1.167
480	**	**	1.216	1.202	1.190	1.171

* Data questionable due to built-up edge possibility.

** Exceeded power of lathe.

Table 5. Stress $S_o \times 10^{-3}$ in psi

Cutting Speed (SFPM)	Rake Angle (degrees)					
	20*	25	30	35	40	45
80	15.0	14.8	15.4	15.4	16.6	18.3
120	15.1	15.3	15.6	15.8	16.6	18.0
160	15.1	15.5	16.2	16.2	16.9	18.1
240	15.2	15.8	16.7	16.9	17.6	18.1
320	15.4	16.3	17.0	17.4	18.2	18.5
480	**	**	16.7	17.3	18.4	18.7

* Data questionable due to built-up edge possibility.

** Exceeded power of lathe.

Table 6. Stress $S_f \times 10^{-3}$ in psi

Cutting Speed (SFPM)	Rake Angle (degrees)					
	20*	25	30	35	40	45
80	66.0	56.8	50.0	41.1	39.0	42.5
120	64.2	52.8	44.0	37.3	35.6	37.9
160	58.7	48.0	40.3	34.1	31.8	34.5
240	51.1	42.1	36.2	30.4	28.4	29.5
320	45.8	37.9	33.2	28.5	27.7	30.3
480	**	**	29.2	26.0	27.6	33.2

* Data questionable due to built-up edge possibility.

** Exceeded power of lathe.

Table 7. Percent Error in Predicting S_f

Cutting Speed (SFPM)	Rake Angle (degrees)					
	20*	25	30	35	40	45
80	+10.8	+0.1	+0.7	+0.7	-5.1	-0.2
120	+1.3	+0.3	+1.7	-0.4	-5.7	+0.5
160	-1.9	-6.2	-0.4	+2.0	+6.5	+1.3
240	+22.2	+5.4	-1.6	+2.6	+1.5	-3.8
320	+24.7	+6.4	-5.2	+4.7	+1.0	-4.6
480	**	**	-8.3	+0.3	+1.4	+1.7

* Data questionable due to built-up edge possibility.

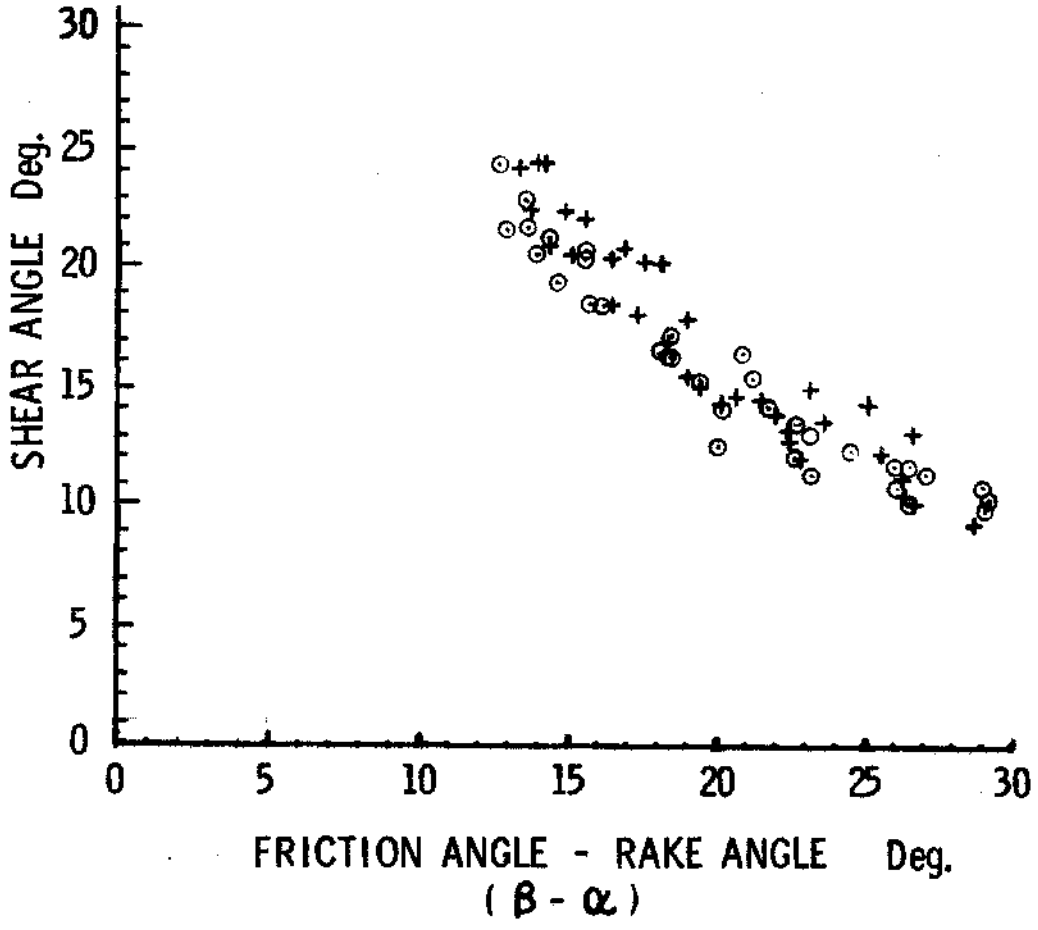
** Exceeded power of lathe.

Table 8. Percent Error in Predicting $\frac{S_s}{S_o}$

Cutting Speed (SFPM)	Rake Angle (degrees)					
	20*	25	30	35	40	45
80	-2.8	+1.0	+0.6	-0.3	-0.9	-0.4
120	+0.3	-0.1	-0.3	-0.5	-0.6	-0.1
160	-0.6	-0.4	-0.2	+0.3	+0.2	+0.2
240	-0.5	-0.1	-0.1	+0.9	+0.6	+0.3
320	-0.8	-0.4	-0.1	+0.7	+0.4	-0.6
480	**	**	-0.2	-0.1	-0.8	-0.7

* Data questionable due to built-up edge possibility.

** Exceeded power of lathe.

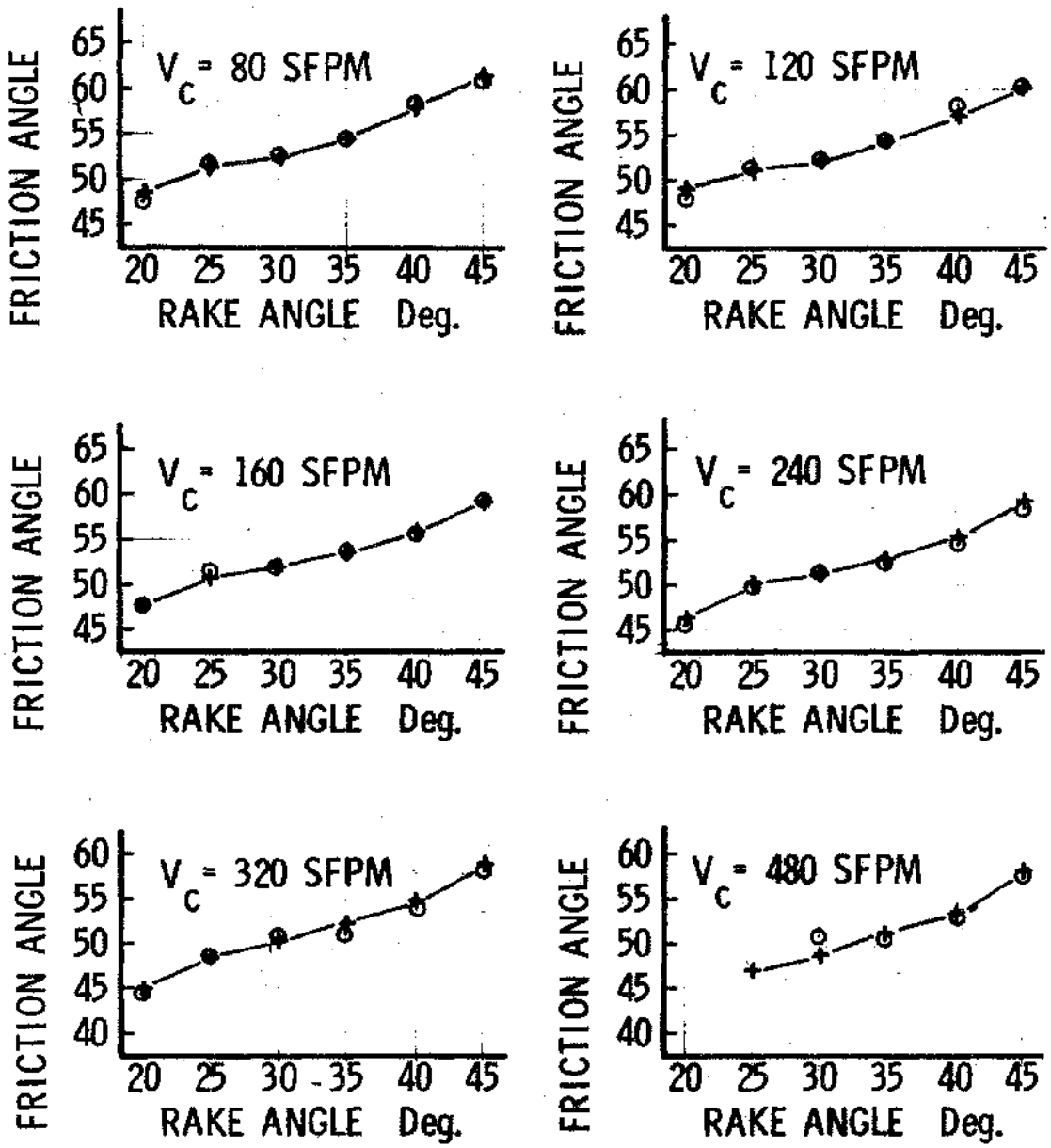


MATERIAL: 1100–O Al; TOOL MATERIAL: HSS

⊙ EXPERIMENTAL DATA POINT

\+ PREDICTED DATA POINT

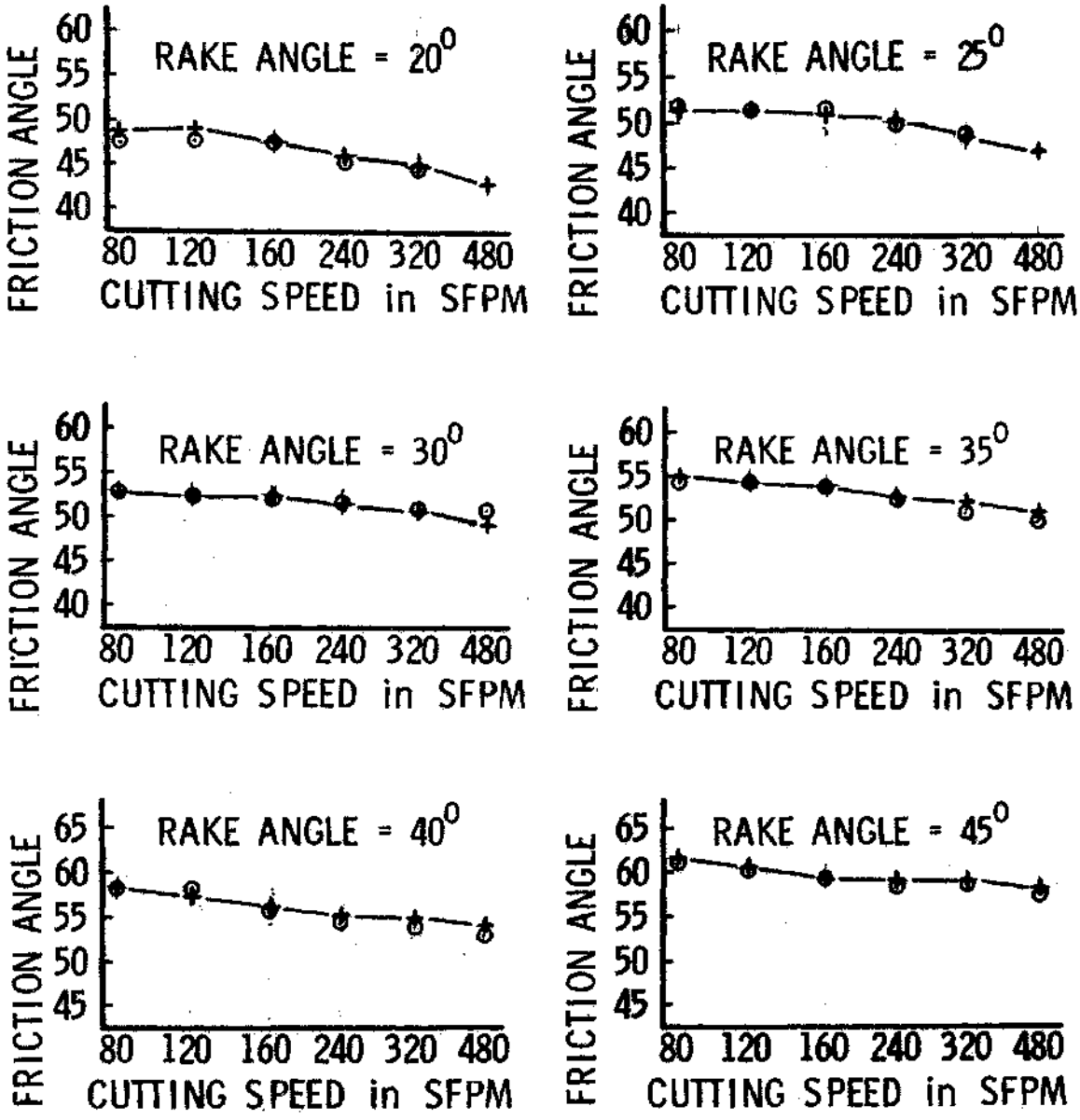
FIGURE 29: SHEAR ANGLE vs. DIFFERENCE BETWEEN FRICTION ANGLE AND RAKE ANGLE



MATERIAL: 1100-O Al; TOOL MATERIAL: HSS; t_1 = 0.0202 ins.

⊙ EXPERIMENTAL DATA POINT; ↖ PREDICTED DATA POINT;

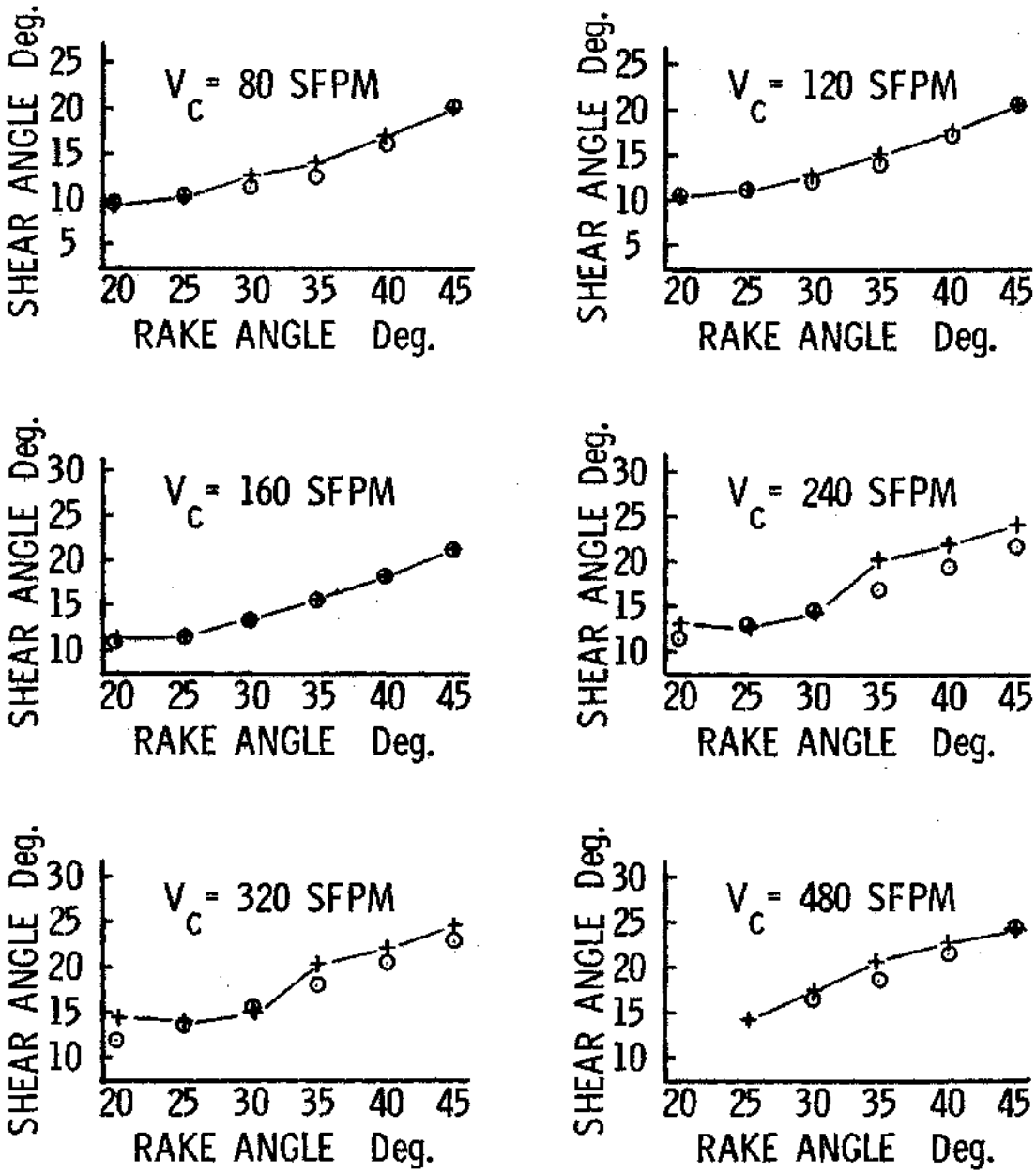
FIGURE 30: FRICTION ANGLE vs. RAKE ANGLE FOR VARIOUS CUTTING SPEEDS



MATERIAL: 1100-O Al; TOOL MATERIAL: HSS; t_1 = 0.0202 ins.

⊙ EXPERIMENTAL DATA POINT; + PREDICTED DATA POINT;

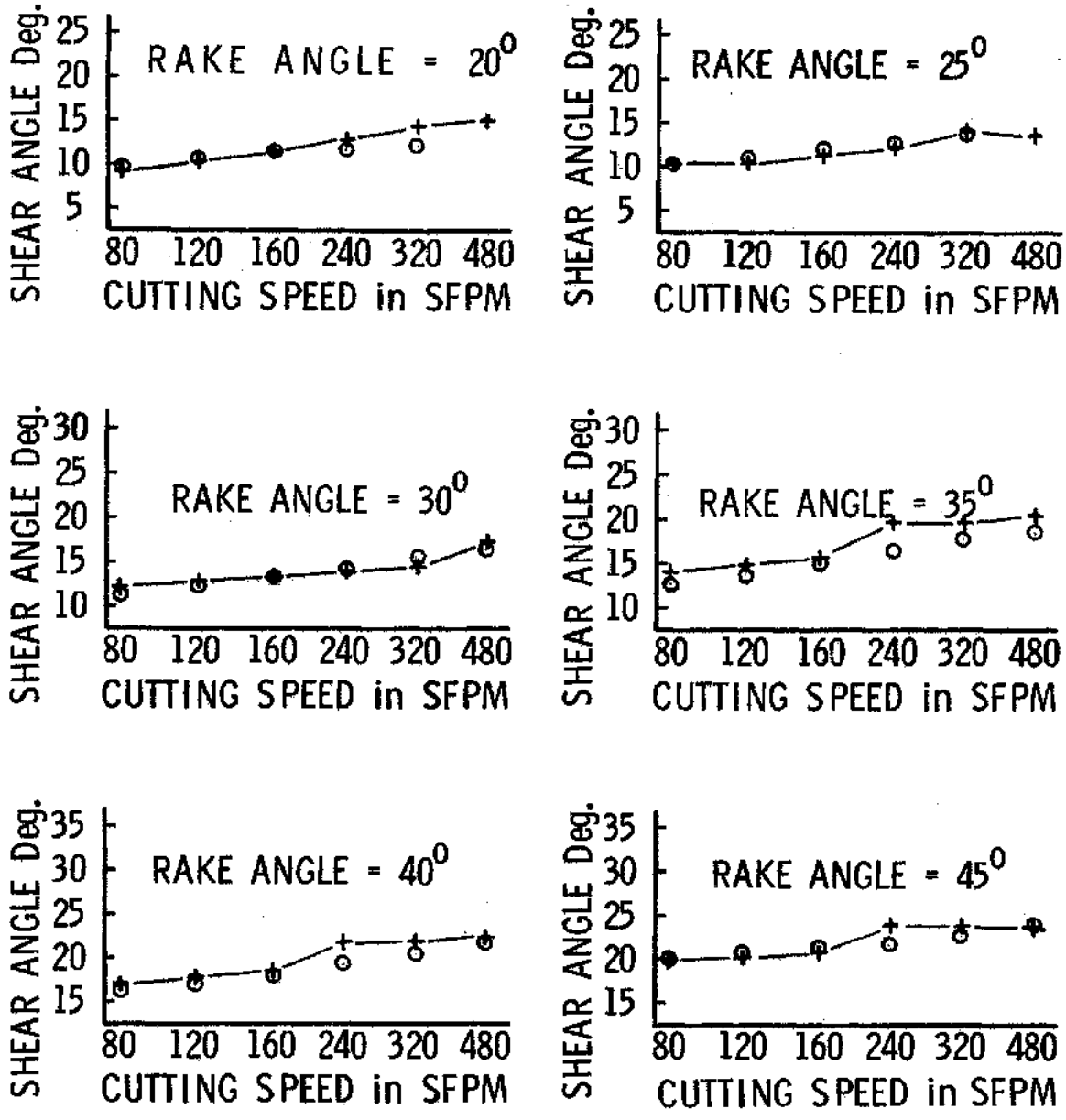
FIGURE 31: FRICTION ANGLE vs. CUTTING SPEED FOR VARIOUS RAKE ANGLES



MATERIAL: 1100-O Al; TOOL MATERIAL: HSS; t_1 = 0.0202 ins.

⊙ EXPERIMENTAL DATA POINT; ✳ PREDICTED DATA POINT;

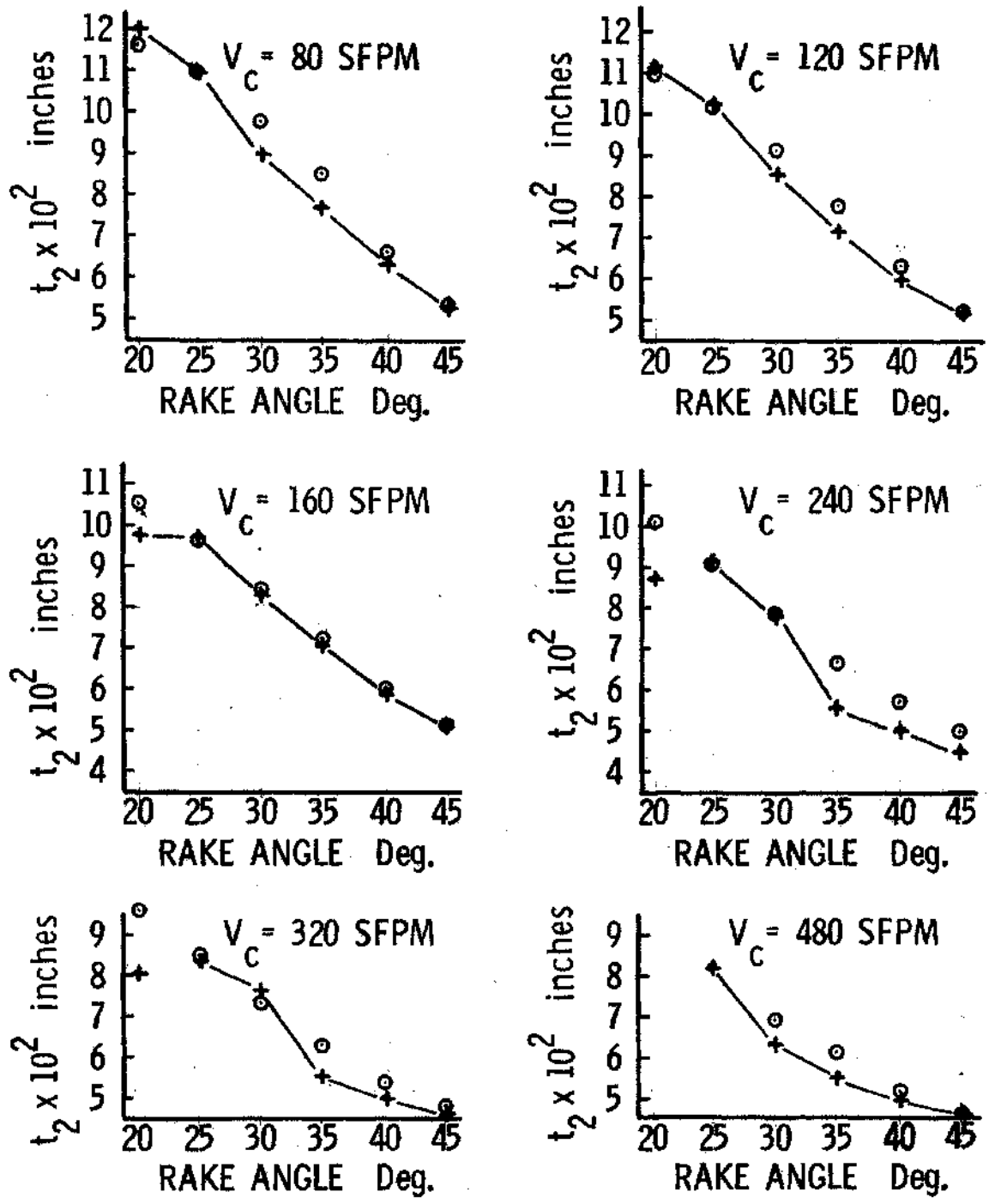
FIGURE 32: SHEAR ANGLE vs. RAKE ANGLE FOR VARIOUS CUTTING SPEEDS



MATERIAL: 1100-O Al; TOOL MATERIAL: HSS; t_1 = 0.0202 ins.

⊙ EXPERIMENTAL DATA POINT; + PREDICTED DATA POINT;

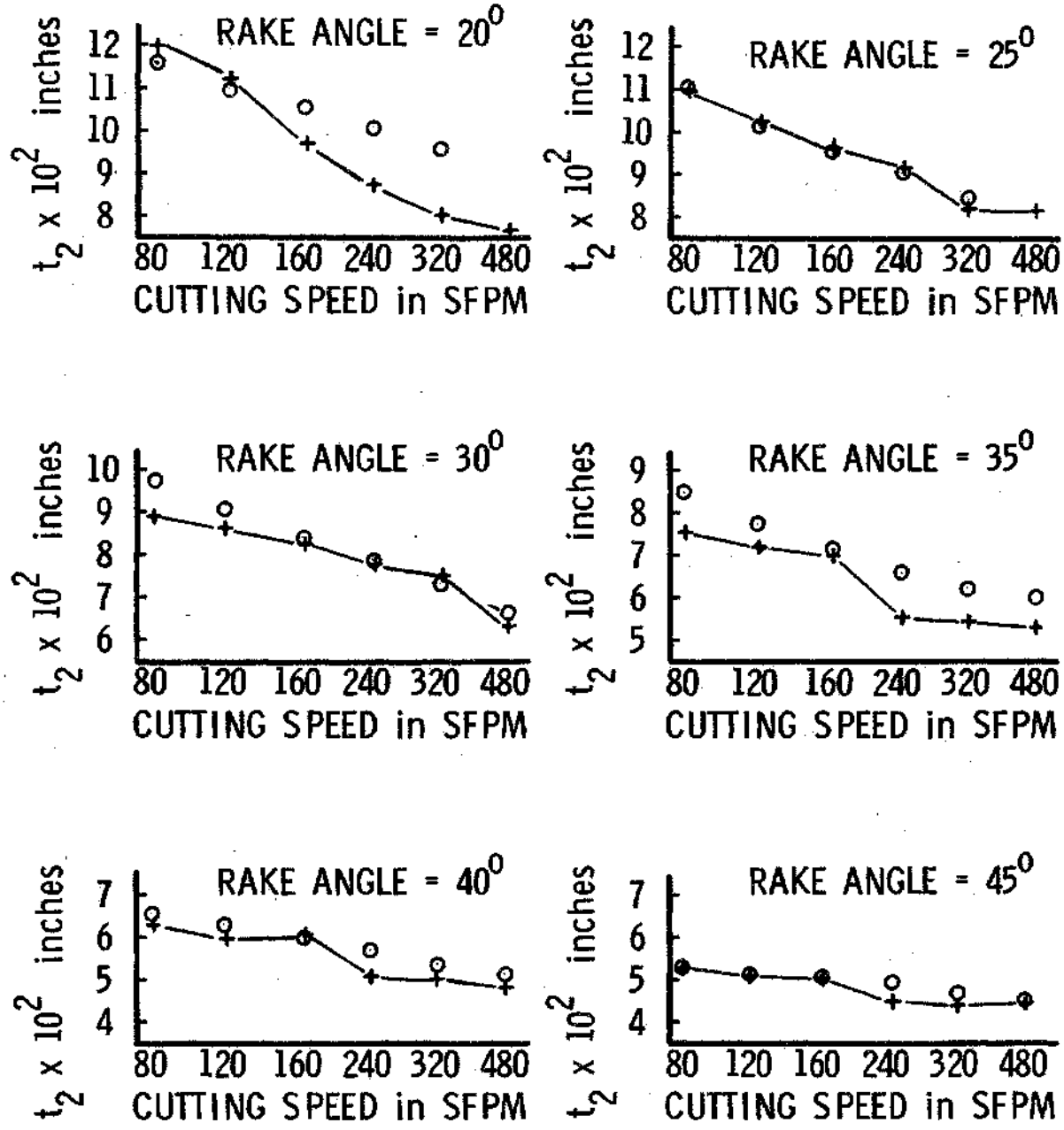
FIGURE 33: SHEAR ANGLE vs. CUTTING SPEED FOR VARIOUS RAKE ANGLES



MATERIAL: 1100-O Al; TOOL MATERIAL: HSS; t_1 = 0.0202 ins.

⊙ EXPERIMENTAL DATA POINT; ⟝ PREDICTED DATA POINT;

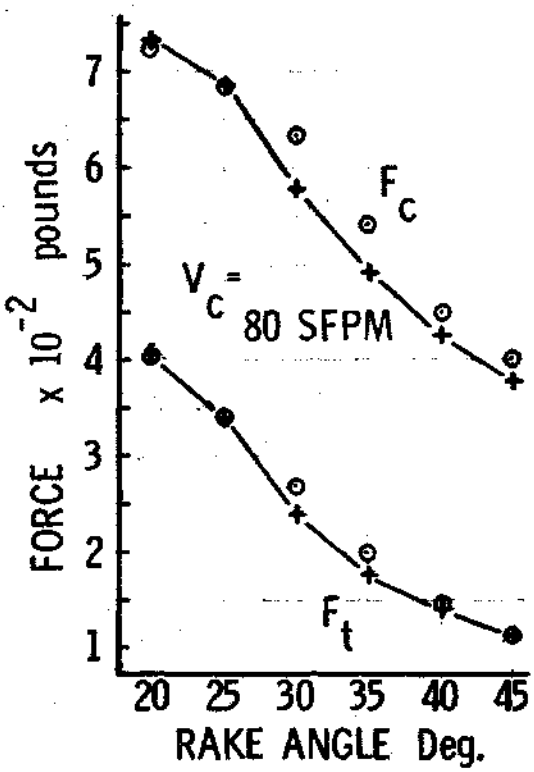
FIGURE 34: CHIP THICKNESS vs. RAKE ANGLE

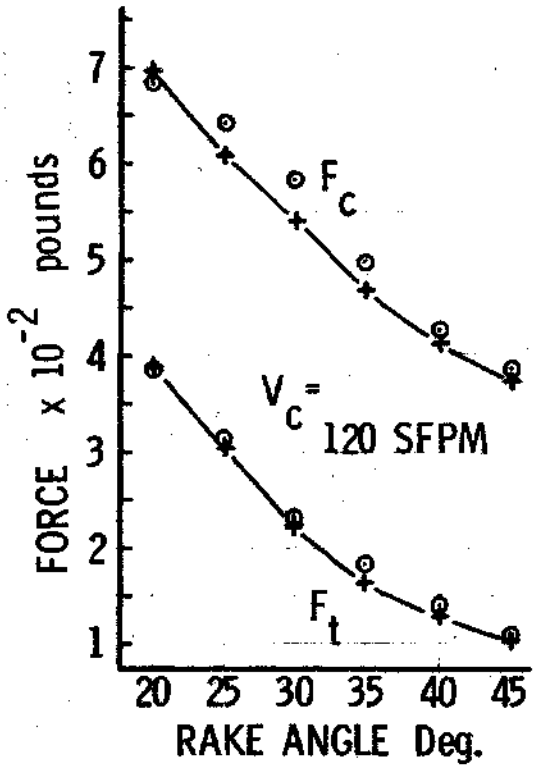


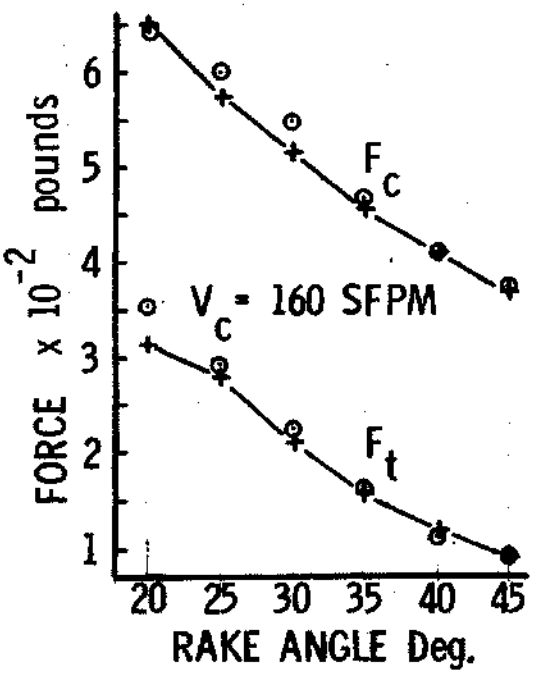
MATERIAL: 1100-O Al; TOOL MATERIAL: HSS; t_1 = 0.0202 ins.

o EXPERIMENTAL DATA POINT; +\ PREDICTED DATA POINT;

FIGURE 35: CHIP THICKNESS vs. CUTTING SPEED







MATERIAL: 1100-O Al;

PREDICTED DATA POINT;

EXPERIMENTAL POINT;

t_1 = 0.0202 ins.

TOOL MATERIAL: HSS;

FIGURE 36a: CUTTING & THRUST FORCE vs. RAKE ANGLE FOR VARIOUS CUTTING SPEEDS

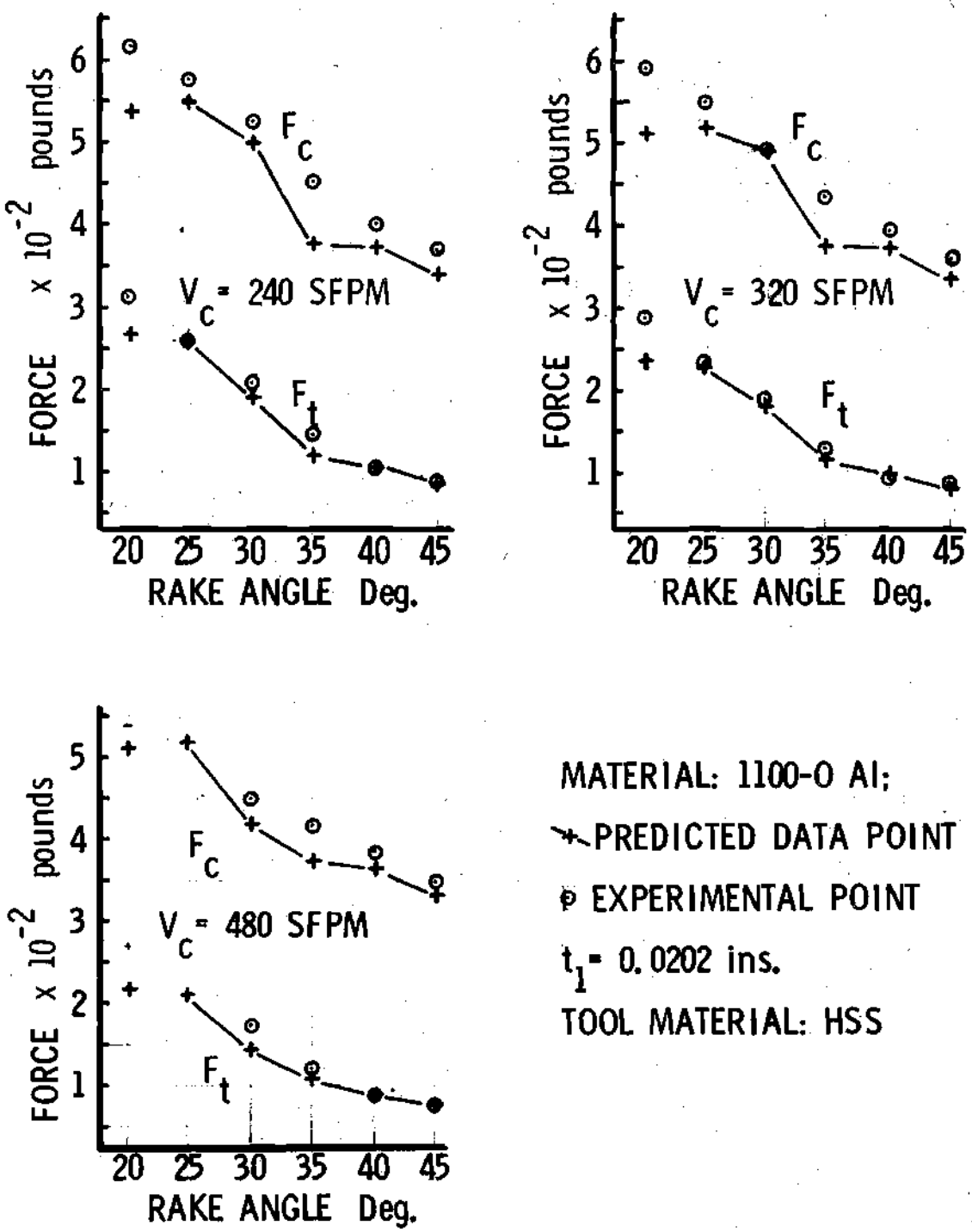


FIGURE 36b: CUTTING & THRUST FORCES vs. RAKE ANGLE FOR VARIOUS CUTTING SPEEDS

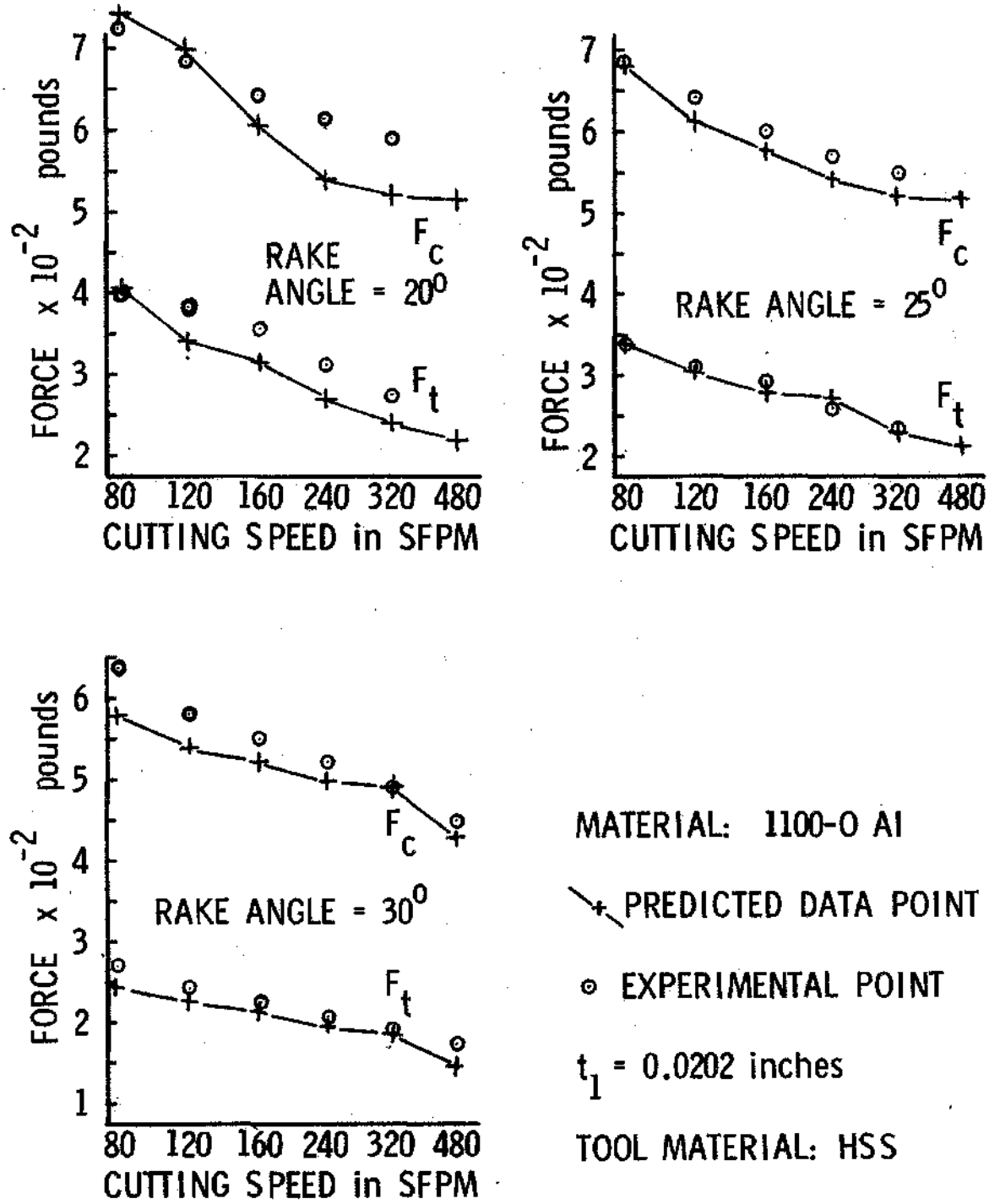


FIGURE 37a: CUTTING AND THRUST FORCES vs. CUTTING SPEED FOR VARIOUS RAKE ANGLES

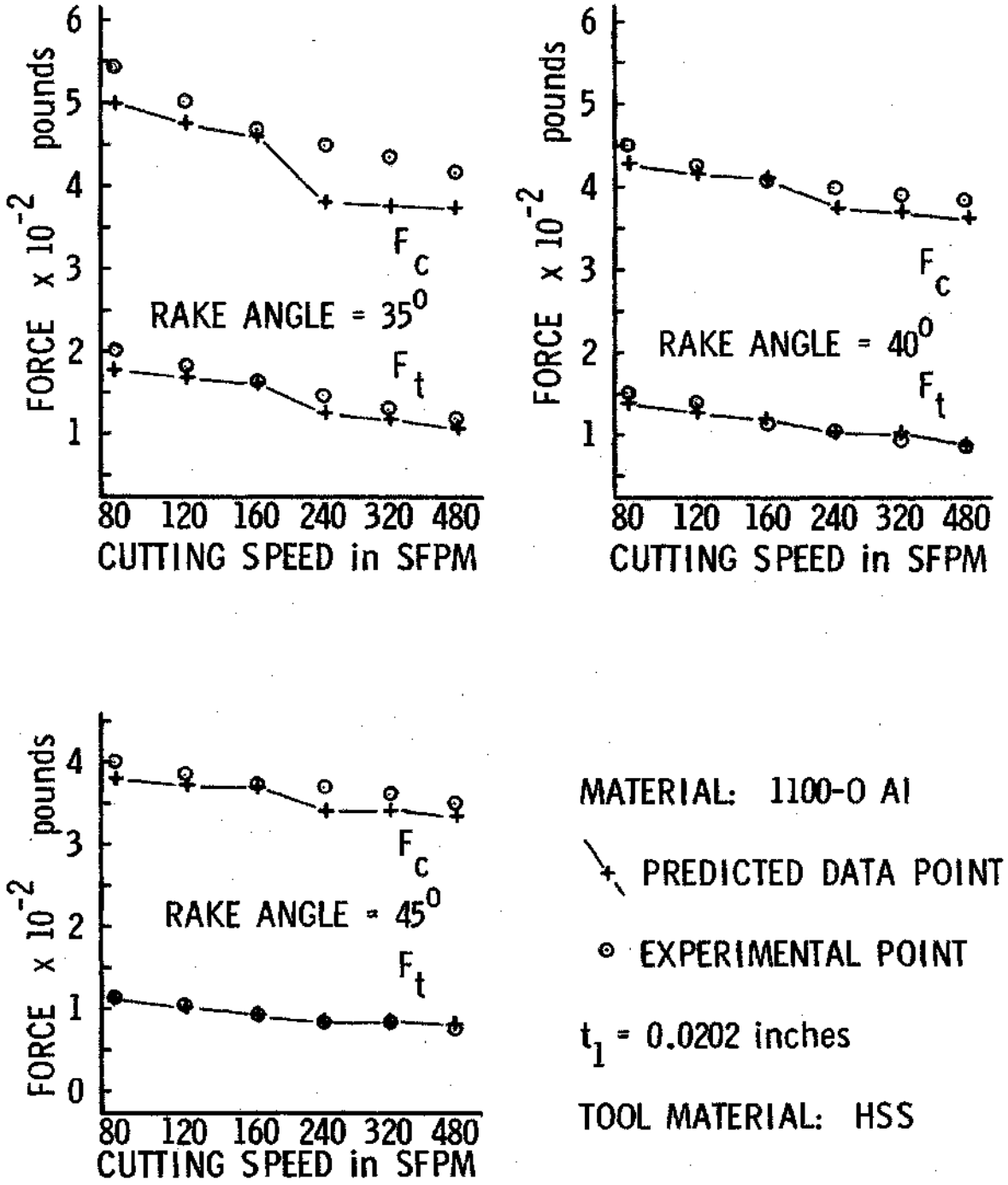


FIGURE 37b: CUTTING AND THRUST FORCES vs. CUTTING SPEED FOR VARIOUS RAKE ANGLES

APPENDIX II

RATE OF WORK IN PRIMARY DEFORMATION ZONE

APPENDIX II

Introduction

An expression is to be derived which will relate the rate of work performed in the Primary Deformation Zone during metal cutting to the stresses and rate of deformation associated with the model of the metal cutting process which has been developed. The following analytical results are not unique in that other solutions may exist and, in fact, may be easily developed. The primary strength of the following analysis is that in use any small errors present when the model is used to investigate the results of a series of experimental tests will be systematic and in turn will be self correcting when the model is used to predict the qualitative results of a series of metal cutting tests.

Development

The initial element is shown in Figure 38 at ABCD, as it would appear prior to deformation. After completely passing through the primary deformation zone the element can be represented by a parallelepiped of width w, height t_2, and base length EF. If ABCD is a rectangular parallelepiped of size $t_1 \times t_1 \times w$, then the length of EF is given by $t_1 \times r_c$ and the deformation can be divided into two portions: (1) hypothetical pure compression from the element ABCD to an element of dimensions $t_2 \times EF$, i.e., a rectangular parallelepiped EFIJ; and, (2) shear deformation of this rectangular element through the angle ν to the condition EFGH.

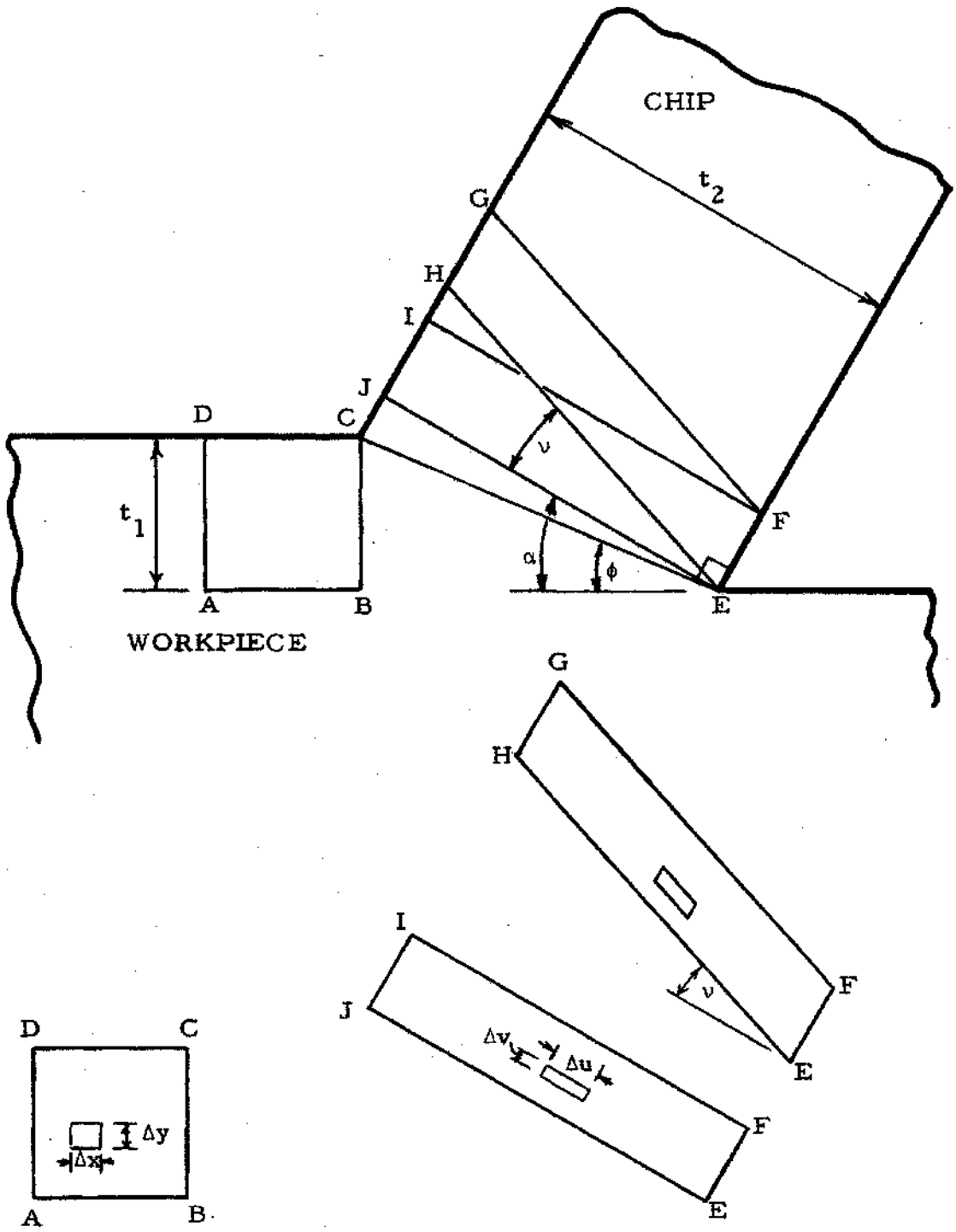


Figure 38: Shear Plane Model Used to Determine Deformation as a Function of Shear and Compression

The work performed in these two separated processes occurs simultaneously and comprises the total amount of work performed in the primary deformation zone. The pure compression deformation results in the chip segment being compressed from dimensions $t_1 \times t_1$ to the dimensions $t_2 \times (r_c \cdot t_1)$ where r_c is the cutting ratio. Figure 38 also shows a chip element before and after being subjected to pure compression. The average normal force on the single element will be

$$\Delta F_{av} = S_{av} \, w \, \frac{\Delta x + \Delta u}{2} \quad , \tag{83}$$

where S_{av} is the average normal stress on the element, and Δx and Δu are defined in Figure 38.

The distance the force ΔF_{av} moves is given by $\Delta y - \Delta v$. Thus, the incremental work performed is given by

$$\Delta W_c = S_{av} \, w \, \frac{(\Delta x + \Delta u)(\Delta y - \Delta v)}{2} \quad . \tag{84}$$

No generality is lost if

$$\Delta y = \Delta x \quad , \tag{85}$$

and since continuity of mass flow must occur, then

$$\Delta v = r_c \, \Delta y \tag{86}$$

and

$$\Delta u = \frac{\Delta x}{r_c} \quad . \tag{87}$$

Substituting into Equation (83) yields

$$\Delta W_c = S_{av}\, w\, \Delta x\, \Delta y \left[\frac{1 - r_c^2}{2\, r_c}\right] \quad , \tag{88}$$

and taking the limit as Δx and $\Delta y \rightarrow 0$ yields

$$dW_c = S_{av}\, w \left[\frac{1 - r_c^2}{2\, r_c}\right] dA \quad . \tag{89}$$

The amount of shear deformation of the element can be represented by the pure shear deformation from condition EFIJ to condition EFGH of Figure 38.

In order to find the amount of shear deformation it will temporarily be assumed that the primary deformation zone can be represented as a shear plane. No generality will be lost in this case because only the amount of shear deformation is of current interest. The mode of shear deformation will be incorporated further into the analysis.

In order to maintain continuity of material flow when an elementary particle travels (Figure 38) from point "D" to point "C" a particle that was at point "A" will have reached point "B." After crossing line CE a particle travels with velocity $V_c\, r_c$, while before it crosses line CE it travels with velocity V_c. Thus, while an element at point B travels from B to E, an element at point C travels from C to H and length CH is given by

$$CH = BE\, r_c \quad , \tag{90}$$

where

$$BE = CE \cos \phi \quad . \tag{91}$$

The angle ν can be found from

$$\tan \nu = \frac{JH}{t_2} \quad , \tag{92}$$

where

$$JH = CH - CJ \quad , \tag{93}$$

and CJ is given by

$$CJ = CE \sin(\alpha-\phi) \quad ; \tag{94}$$

and finally,

$$\cos(\alpha-\phi) = \frac{t_2}{CE} \quad . \tag{95}$$

Substituting for JH and CH in Equation (92) and simplifying gives:

$$\tan \nu = \frac{r_c \cos \phi - \sin(\alpha-\phi)}{\cos(\alpha-\phi)} \quad . \tag{59}$$

If the shear stress of deformation of the element of Figure 38 is assumed to be equal to S_{av}, then the elemental work performed will be

$$\Delta W_s = S_{av} \, w \, \Delta u \, \Delta v \tan \nu \quad , \tag{96}$$

and taking the limit as the element size approaches zero yields

$$dW_p = S_{av}\, w \left[\frac{1 - r_c^2}{2\, r_c} + \tan \nu \right] dA \quad , \tag{97}$$

where

$$dW_p = dW_c + dW_s \quad . \tag{98}$$

The average velocity of an element in passing through the primary deformation zone is given as

$$V_{av} = \frac{V_c\ (1+r_c)}{2} \quad ; \tag{99}$$

the average distance an element travels as it passes through the primary deformation zone (Figure 27) is approximately

$$D = \frac{1}{2}\, AB\ (\Psi+\alpha-\xi) \quad , \tag{100}$$

where $(\Psi+\alpha-\xi)$ is expressed in radians. Thus, the average time required for an element to pass through the primary deformation zone is given as the distance divided by the velocity, or

$$T_{rq} = \frac{AB\ (\Psi+\alpha-\xi)}{V_c\ (1+r_c)} \quad . \tag{55}$$

If the elementary work is summed over the entire area of the primary deformation zone and it occurs at a rate dependent on the average time required to pass through that zone, then the work per unit time occurring in the primary deformation zone is given as:

$$W_{pt} = S_o \, w \left[\frac{1 - r_c^2}{2 \, r_c} + \tan \nu \right] \frac{A_{pdz}}{T_{rq}} \quad , \qquad (54)$$

where the average stress of the primary deformation zone is assumed to be S_o.

APPENDIX III

LIST OF SYMBOLS USED

APPENDIX III

LISTING OF ALPHABETICAL SYMBOLS USED

A_o	cross-sectional area of undeformed chip
A_{pdz}	area of primary deformation zone
dA	incremental area
AB	Plane AB, length of that plane
BD	Plane BD, length of that plane
BE	Plane BE, length of that plane
BF	Plane BF, length of that plane
BG	Plane BG, length of that plane
BGC	lower boundary of Primary Deformation Zone
C	machining constant
CE	Plane CE, length of that plane
CG	Plane CG, length of that plane
CH	Plane CH, length of that plane
CJ	Plane CJ, length of that plane
d	small length of Primary Deformation Zone, Figure 27
D	average distance through Primary Deformation Zone
DF	Plane DF, length of that plane
F_c	cutting force component of resultant forces of cutting
F_n	normal force on shear plane
F_t	thrust force component of resultant forces of cutting

G	a dimensionless constant
h	small length of Primary Deformation Zone, Figure 27
JH	Plane JH, length of that plane
K	slope of shear stress versus normal stress curve
k	thermal conductivity of workpiece material
k	yield shear stress
l_s	length of shear plane
l_o	chip-tool contact length
$\bar{N}$	component of resultant cutting force acting normal to tool face
N	a dimensionless constant, the ratio of normal to shear stress acting on Plane BF; equal to 1
N_f	normal stress acting on chip-tool contact area
N_o	normal stress acting on Planes BE and BD
N_s	normal stress acting on Plane AB
P	tool nose force
P_A	hydrostatic stress at point A
P_B	hydrostatic stress at point B
P_s	specific cutting pressure
q_f	heat generated through "friction" at chip-tool interface
q_s	heat generated through shearing in Primary Deformation Zone
q_{tl}	total heat generated during metal cutting
r_c	cutting ratio
R	resultant tool force

S	shear stress on shear plane
S_{av}	average stress acting on element during deformation
S_o	shear stress intercept with zero normal stress on shear plane
S_o	shear stress on Planes BD and BE
S_n	normal stress on shear plane
S_i	initial shear strength of workpiece material
S_f	shear stress at chip-tool interface
S_s	shear stress along Plane AB and Plane BF of proposed model
T	temperature
T_{rq}	average time required for an element to pass through the Primary Deformation Zone
t_1	undeformed chip thickness
t_2	chip thickness
V_c	cutting speed
w	width of chip and workpiece
W_{kf}	work per unit time performed through "friction" forces
W_{pd}	work per unit time performed in Primary Deformation Zone as a function of the forces of cutting and the cutting velocity
W_{pt}	work per unit time performed in Primary Deformation Zone as a function of the stresses and deformation of that zone
W_{tl}	total work per unit time performed during cutting

Listing of Greek Symbols Used

α	rake angle
β	friction angle

β_s fraction of heat generated in Primary Deformation Zone that is transmitted to workpiece

δ angle parameter of proposed model

Δu incremental length

Δv incremental length

ΔW_c incremental work performed by compression

ΔW_s incremental work performed by shear

Δx incremental length

Δy incremental length

ϵ strain

$\dot{\epsilon}$ strain rate

η angle between shear plane and direction of maximum shear stress after Shaw, et al.[9]

Γ dimensionless constant

γ shear angle parameter of proposed model

$\dot{\gamma}_i$ generalized shear strain rate

γ_s shear strain in metal cutting

$\dot{\gamma}_1$ average strain rate of Primary Deformation Zone

$\dot{\gamma}_2$ average strain rate of Secondary Deformation Zone

μ coefficient of friction

ω an angle parameter after Huck[8]

ϕ shear angle

Ψ angle parameter of proposed model

ρ density of workpiece material

σ stress

σ_o a stress constant

τ shear stress

τ_i individual shear stress

θ angle parameter after Palmer and Oxley[18]

θ thermal number

θ_f average temperature rise of the chip due to "friction" at the chip-tool interface

θ_{ma} maximum temperature rise of the chip above ambient temperature at the chip-tool interface

θ_{mx} maximum temperature rise of the chip due to "friction" at the chip-tool interface

θ_s average temperature rise of the chip as a result of shear deformation in the Primary Deformation Zone

θ_{ts} maximum possible average temperature rise of the chip due to deformation in the Primary Deformation Zone

ν angle of shear deformation required to maintain mass flow continuity

ξ angle parameter of proposed model

APPENDIX IV

COMPUTER PROGRAMS

APPENDIX IV

Introduction

The following computer programs were used to determine the applicability of the model, analyze experimental results, and then predict the trends inherent to the metal cutting process.

The first program, called PR 6 PROCEDURE OPTIONS (MAIN), reads experimental metal cutting data from a single test in step number 38. The model is then used to analyze this data and, after determination of an applicable geometry is made, the output is printed in steps 311 to 319. This process is repeated until no data is found in the data storage and the condition END FILE exists. Computation then terminates.

The second program, called PR 4 PROCEDURE OPTIONS (MAIN), has several subroutines in it. One of these subroutines, called FNCTN, beginning in step number 405 defines the model developed in this work. The preceding 400 steps are required to define the problem and provide a complex iterative procedure required to select the proper geometry which will satisfy all of the constraints of the system.

The third program, called PR 2 PROCEDURE OPTIONS (MAIN), is used to determine the appropriate constants for Equation (79). Several equations are tried of the forms proposed by various workers[15,24,21], and that proposed by Lubahn[21] was found to approximate closely the final conditions. Slight modification of this equation resulted in Equation (79).

PR6: PROCEDURE OPTIONS (MAIN)

```
1                PR6: PROCEDURE OPTIONS (MAIN)                                                    ;
2                ON ENDFILE (SYSIN) GO TO LBL                                                     ;
4                ON ZERODIVIDE  GO TO LB1                                                         ;
6                DECLARE I DECIMAL (8) , K DECIMAL , LAB DECIMAL,LBE DECIMAL (9) ,
                       LBF DECIMAL (9) , LO DECIMAL (9) , LT1R DECIMAL , LT2R DECIMAL
                       , NOSO DECIMAL , NS DECIMAL (10) , KE1 DECIMAL , KE2 DECIMAL ;
7                DECLARE ( LBC , NI  ,KSP,N                                  ) DECIMAL  ;
8                DECLARE ZH(30) , H0(35) , H1(35) , LBH DECIMAL                               ;
9                DECLARE ( HH,GG,TT,V,JJ,KK,CT          ) BINARY FIXED                        ;
10               DECLARE R0(25) ,CH(25)                                                       ;
11              DECLARE AR1(50,10),AR2(50,10),P0(45),P1(45),P2(25),PS(45),G0(25)              ;
12               DECLARE R1(25)                                                               ;
13               DECLARE DL(20) , RS(20),G1(25)                                               ;
14              FMTCR: FORMAT (  12 F(10,4)  )                                                ;
15              FMT01: FORMAT (2F(9,1),F(9,3),2F(9,4),2F(9,1),2F(9,2), 4F(9,0),A(3))          ;
16              FMT02: FORMAT (3F(10,3) ,3F(10,3) ,5F(10,1), F(10,4)          )               ;
17              FMT03: FORMAT (4F(10,4) ,2F(10,0) , F(10,2),2F(10,2), 8F(10,0)       );
19              DTA2:  FORMAT (X(1),F(7,1), X(2) , F(6,2) , X(2) , F(6,3) , X(2) ,
                     F(6,4),X(2),F(7,5),X(2),F(6,4),X(2),2(F(5,2),X(2)),F(15,5)     );
19              DTA3:  FORMAT (X(1),F(7,1), X(2) , F(6,2) , X(2) , F(6,3) , X(2),X(48),
                     F(6,4),X(2),F(7,5),X(2),F(6,4),X(2),2(F(5,2),X(2)),F(7,5)       );
20               L = 0 ;
21               SSN = 25000                                                                  ;
22               SON = 25000                                                                  ;
23                SSSON = 2 ; PSIDN = 45 ;
25               PI  = 3.1415926536                                                           ;
26               DTR = PI/180.0                                                               ;
27               RTD = 180.0/PI                                                               ;
28               P   = 0.0975                                                                 ;
29               K   = 10.81                                                                  ;
30               CP  = 0.243                                                                  ;
31               SII = 15000                                                                  ;
32               NOSO = 1.0                                                                   ;
33               TT  = 0                                                                      ;
34               C34 = 1.0                                                                    ;
35              LB0:
                 IF MOD(L,5) = 0 THEN
36               PUT EDIT ('.') (PAGE , X(119) , A(1) )                                       ;
37               L = L + 1 ;
38              GET EDIT (   I,VC,ALPD,W,T1,T2,RCM,RTM,CLO )  ( R(DTA2)                      );
39               PSID = 0.0005                                                                ;
40               JC = 10                                                                      ;
41               J = 0                                                                        ;
42               GG = 0                                                                       ;
43               CT = 0                                                                       ;
44               HH = 1                                                                       ;
45               ALPD= ALPD                                                                   ;
46               IF ALPD < 26 THEN PSID = 10.005                                              ;
48               ALPR = ALPD * DTR                                                            ;
49               PT  = 17.4*RTM                                                               ;
50               PC  = 16.7*RCM                                                               ;
51               RC  = T1/T2                                                                  ;
52               FIT = (RC * COS(ALPR))/( 1 - RC*SIN(ALPR))                                   ;
```

```
PR6: PROCEDURE OPTIONS (MAIN)

53              PFIR=    ATAN(FIT)   ; PFID = PFIR*RTD                                    ;
55              QP   = VC*RC*(FC*SIN(ALFR) + FT*COS(ALFR))/1400                           ;
56              THP  = QP/(12*P*CP*VC**T1*W)                                              ;
57              QS   = FC*VC/1400 - QP                                                    ;
58              R    = 720*P*CP*VC*T1/F                                                   ;
59              THNB= R*FIT  ; THNB = ABS(THNB)                                           ;
61              IF THNB > 12.0  THEN BETA = 0.10;ELSE BETA = 0.475 - 0.1498*LOG(THNB);
64              THS  = QS*(1-BETA)/(12*P*CP*VC*T1*W)                                      ;
65              TTHS= THS/(1-BETA)                                                        ;
66              BER = ALFR +   ATAN(FT/FC)    ;  BED = BER*RTD                           ;
68              F    = FC*SIN(ALFR) + FT*COS(ALFR)                                        ;
69              FN   = FC*COS(ALFR) - FT*SIN(ALFR)                                        ;
70              WTL = FC*VC                                                               ;
71              WKF = F*VC*RC                                                             ;
72              WPD = WTL - WKF                                                           ;
73              THT =   ATAN((RC*COS(PFIR) - SIN(ALFR-PFIR))/(COS(ALFR-PFIR)))           ;
74              THT = ATAN((RC*COS(PFIR) - SIN(ALFR-PFIR))/(COS(ALFR-PFIR)))             ;
75              TTHT=       ((RC*COS(PFIR) - SIN(ALFR-PFIR))/(COS(ALFR-PFIR)))           ;
76              TTHT = ABS(TTHT)                                                          ;
77              THTD= THT*RTD                                                             ;
78              SSSO= 1.40                                                                ;
79             LB3:
80              IF J > JC THEN GO TO LB5                                                  ;
81              CT = CT + 1                                                               ;
82              IF CT > 51 THEN GO TO LB1                                                 ;
84              IF TT > 40 THEN GO TO LBL  ;
86              SSSOH= SSSO    ;
87              PSIR = PSID*DTR                                                           ;
88              Y = ((FT/FC-1)*COS(ALFR+PSIR) + (FT/FC+1)*SIN(ALFR+PSIR))/(SSSO*
                                                                          SIN(PSIR))    ;
89              DELR = ATAN((Y*COS(ALFR) + FT/FC - WOSO )/(Y*SIN(ALFR)+WOSO*FT/FC+1));
90              DELD = DELR*RTD                                                           ;
91              PSYD = PSID                                                               ;
92              SSSO= SSSOH                                                               ;
93              PP   = 1.0 + (SIN(PSIR))/(COS(PSIR))                                     ;
94              PM   = 1.0 - (SIN(PSIR))/(COS(PSIR))                                     ;
95              CPPS= COS(PSIR) + SIN(PSIR)                                               ;
96              ZZ   = RC +((((SIN(PSIR))*(SIN(DELR)))/((COS(DELR+ALFR))*CPPS)))         ;
97              GMT  = (ZZ*(COS(ALFR))/((1.0/PP) - ZZ*(SIN(ALFR))))                      ;
98              GMR =   ATAN(GMT)   ; GMD = GMR*RTD                                      ;
100             SSSO= (PP*COS(GMR-ALFR) - PM*SIN(GMR-ALFR))*COS(GMR-ALFR)                ;
101             IF CT = 1 THEN GO TO LB3                                                  ;
103             LT2R= COS(PSIR+ALFR+DELR)/(CPPS*COS(ALFR+DELR))          ;
104             LT1R= LT2R/RC                                                             ;
105             LO   = LT1R*T1                                                            ;
106             LBE  = T2/CPPS                                                            ;
107             LBF  = (LBE*(SIN(PSIR)))/(COS(ALFR+DELR))                                ;
108             LAB  = LBE*(COS(PSIR))/(COS(GMR-ALFR))                                   ;
109             BCAB = (SIN(GMR))/(SIN(2*GMR-ALFR-PSIR))                                 ;
110             LBC  = LAB*BCAB                                                           ;
111             SSSOH=SSSO       ;
112             SO   = FC/(W*(LBE*(SIN(PSIR+ALFR) + COS(PSIR+ALFR)) +
                        SSSO*LBF*(COS(DELR) - WOSO*(SIN(DELR)))))                       ;
```

```
PR6: PROCEDURE OPTIONS (MAIN)

113             SFSO= (PM/(PP-1) + SSSO*(SIN(ALFR+DELR)/COS(ALFR+DELR) + NOSO))/
                (1/(PP-1) - SIN(ALFR+DELR)/COS(ALFR+DELR))                        ;
114              SSSO=SSSOH   ;
115             SFT1= SFSO*SO                                                     ;
116             SS = SO*SSSO                                                      ;
117             R  = (SIN(PPIR-ALFR))/(COS(PPIR-ALFR)) +(COS(PPIR))/(SIN(PPIR)) ;
118             B  = SQRT(ABS(R/LT2R))                ;
119             THMX= 0.72*THF*B*(0.856**(B*LT2R*(PP-1)/2.5))                     ;
120             THMA= THMX + THS                                                  ;
121             FS  = F/(LO*W)                                                    ;
122             NS = (COS(PSIR+ALFR-GMR)-SIN(PSIR+ALFR-GMR))*SO*LBE/LAB           ;
123             ET1 = 0.1*E*VC*(1 + RC)/(LBE*(PSIR+ALFR-GMR))                     ;
124             ET2 = 0.4*VC*RC/(LO*(PP-1))                                       ;
125             IF ET2 <  0.0001 THEN ET2 = 1.0                                   ;
127             SFT2= 477*(E**1.577)*( ET2**0.290)                                ;
128             N = 1                                                             ;
129             CH(1) = 15.0                                                      ;
130             CH(2) = 20.0                                                      ;
131            LB6;
132               IF CH(N) > GMD THEN CH(N) = 10                                 ;
133               IF CH(N) < 0.01 THEN CH(N) = 2                                ;
135              CHID = CH(N)                                                     ;
136             CHIR = CHID*DTR                                                   ;
137             AA = (2*COS(CHIR))*(SIN(GMR) - SIN(CHIR)) + 1.0                   ;
138             DD = SS*COS(GMR-CHIR) + NS*SIN(GMR-CHIR)                          ;
139             SI = DD/AA                                                        ;
140             RO(N) = SI - SII                                                  ;
141             IF N = 1 THEN DO ; N = 2 ; GO TO LB6 ; END                        ;
146             IF ABS(RO(N)) > 1.0 THEN DO                                       ;
148             R1(N) = (RO(N)-RO(N-1))/(CH(N) - CH(N-1))                         ;
149             CH(N+1) = CH(N) - RO(N)/R1(N)                                     ;
150             N = N + 1                                                         ;
151             IF N > 25 THEN GO TO LB1                                          ;
153             GO TO LB6                                                         ;
154             END /* IF RO(N)> 1.0     */                                      ;
155             H = LAB*(SIN(GMR) - SIN(CHIR))                                    ;
156             D = LAB*(COS(CHIR) - COS(GMR))                                    ;
157             CC = NS*COS(GMR-CHIR) - SS*SIN(GMR-CHIR)                          ;
158             NI = CC                                                           ;
159             APDZ = (LAB**2)*(PSIR+ALFR-CHIR)/2 + H*(H+D)/2                    ;
160             TRQ = LAB*(PSIR+ALFR-CHIR)/(VC*(1+RC))                            ;
161             WPT =  SO*W*((1-RC**2)/(2*RC) + TTHT)*APDZ/TRQ                    ;
162             RE2 = WPD - WPT                                                   ;
163             IF GG > 0 THEN DO                                                 ;
165               FO(J) = WPD - WPT                                               ;
166               IF ABS(FO(J)) < WPD/5000   THEN GO TO LB5                       ;
168               END                                                             ;
169             IF J > 2 THEN F1(J) = ( FO(J) - FO(J-1))/(PS(J) - PS(J-1))        ;
171             IF GG = 5 THEN GO TO LB5                                          ;
173             IF GG = 0 THEN DO                                                 ;
175               IF WPT<WPD THEN DO                                              ;
177                 IF J = 0 THEN DO                                              ;
179                 J = 1                                                         ;
```

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PR6: PROCEDURE OPTIONS (MAIN)

180                   GG = 1                                                    ;
181                   PS(1) = PSID + 1                                          ;
182                   DO N = 1 TO 16                                            ;
183                   PS(N) = PS(1) + 1 - N                                     ;
184                    END                                                      ;
185                   END                                                       ;
186                 JC = J + N                                                  ;
187                 END                                                         ;
188               END                                                           ;
189               IF GG = 0 THEN DO                                             ;
191               IF PSID < 85 THEN DO ; PSID = PSID + 5 ; GO TO LB3  ;END      ;
196               IF J = 0 THEN GO TO LB1                                       ;
198               END                                                           ;
199               IF GG = 1 THEN DO                                             ;
201                 IF WPT > WPD THEN DO                                        ;
203                 GG = 2                                                      ;
204                     DO N = 1 TO 14                                          ;
205                     PS(J+N) = PS(J) - 0.4 + N/5                             ;
206                     END                                                     ;
207                 JC = J + N                                                  ;
208                 END                                                         ;
209               J = J + 1                                                     ;
210               PSID = PS(J)                                                  ;
211               GO TO LB3                                                     ;
212               END                                                           ;
213               IF GG = 2 THEN DO                                             ;
215                 IF WPT<WPD THEN DO                                          ;
217                   DO N = 1 TO 15                                            ;
218                   PS(J+N) = PS(J) + 0.12 - 0.08*N                           ;
219                   GG = 3                                                    ;
220                   END                                                       ;
221                 JC = J + N                                                  ;
222                 END                                                         ;
223               J = J + 1                                                     ;
224               PSID = PS(J)                                                  ;
225               GO TO LB3                                                     ;
226               END                                                           ;
227               IF GG = 3 THEN DO                                             ;
229                 IF WPT>WPD THEN DO                                          ;
231                   DO N = 1 TO 19                                            ;
232                   PS(J+N) = PS(J) - 0.02 + 0.005*N                          ;
233                   GG = 0                                                    ;
234                   END                                                       ;
235                 JC = J + N                                                  ;
236                 END                                                         ;
237                 J = J + 1                                                   ;
238                   PSID = PS(J)                                              ;
239                   IF ABS(F0(J-1))> 10.0 THEN GO TO LB3                      ;
241               END                                                           ;
242               IF GG = 4 THEN DO                                             ;
244                 IF WPT<WPD THEN DO                                          ;
246                 PS(J+1) = PS(J) - F0(J)/F1(J)                               ;
247                 GG = 5                                                      ;
```

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PR6: PROCEDURE OPTIONS (MAIN)

248                 END                                                                ;
249                 J = J + 1                                                          ;
250                 PSID = PS(J)                                                       ;
251               GO TO LB3                                                            ;
252               END                                                                  ;
253             LB5:
                  RR =(H + D + LAB*COS(GMR) - LBE*COS(PSIR + ALFR))/COS(ALFR)        ;
254               N = 1                                                                ;
255               ZH(1) = 10.0 ; ZH(2) = 15.0                                          ;
257             LB2:
                  IF ZH(N) > (90.0-ALFD) THEN ZH(N) = 40                             ;
259               IF ZH(N) < 0.01 THEN ZH(N) = 2.0                                     ;
261               ZHID = ZH(N)                                                         ;
262               ZHIR = ZHID*DTR                                                      ;
263               AG =  COS(ALFR)/COS(GMR) - SIN(ALFR)/SIN(GMR) +
                        LBE*(COS(PSIR+ALFR)/COS(GMR) - SIN(PSIR+ALFR)/SIN(GMR))/RR   ;
264               HO(N) = SIN(ZHIR)/COS(ZHIR) - COS(ZHIR)/SIN(GMR) - AG              ;
265               IF N = 1 THEN DO ; N = 2 ; GO TO LB2 ; END                         ;
270               IF ABS(HO(N) ) > 0.0001 THEN DO                                    ;
272               H1(N) = (HO(N) - HO(N-1))/(ZH(N)-ZH(N-1))                          ;
273               ZH(N+1) = ZH(N) - HO(N)/H1(N)                                      ;
274               N = N+1                                                            ;
275               IF N>25 THEN GO TO LB4                                             ;
277               GO TO LB2                                                          ;
278               END /* IF HO(N) > 0.0001   */                                      ;
279             LB1:
                  LBH = ( H + D + LAB*COS(GMR) - RR*SIN(ZHIR) )/COS(GMR)             ;
280               TSS = LAB*SS/LBH                                                   ;
281             LB4:
282               SKO = 1.12033 ; GK = 6.08377 ; T = TTHS/1000 ; AA = -.0123976 ;
285               BB = 0.340303 ;   CC = -0.16177 ;
287               SSSOP = SKO*(GK**T)*(E**(AA+BB*T))*(ET1**(CC*T))                   ;
288               SSK = 15830 ; GSK = 8305.47 ; AAS = -0.492552 ; BBS = -2.16237 ;
292               CCS = -0.120091 ;
293               SSP = SSK*(GSK**T)*(E**(AAS+BBS*T))*(ET1**(CCS*T))                 ;
294               SOP = SSP/SSSOP ;
295               T = TMMA/1000 ;
296               SPO = EXP(14.1042) ;
297               GK = EXP(-13.2560 ) ;
298               AA = -1.84670 ;
299               BB = 15.7909 ;
300               CC = -0.246249 ;
301               DD = 1.19791 - 1.36858*(LOG(E)) ;
302               SPE1 = SPO*(GK**T)*(E**(AA+BB*T))*(ET2**(CC+DD*T))    ;
303               SPT2 = SPE1 ;
304                 SPT3 = SPT2*SOP/SO                                               ;
305               SPSOP = SPT1/SOP                                                   ;
306               ESOP = 100*(SOP-SO)/SO                                             ;
307               ESSP = 100*(SSP-SS)/SS                                             ;
309               ESSSOP = 100*(SSSOP-SSSO)/SSSO                                     ;
309               ESPT2 = 100*(SPT2-SPT1)/SPT1        ; ESPT3 = 100*(SPT3-SPT1)/SPT1 ;
311             PUT EDIT ( ' ITERATIONS ON TEST NUMBER ', I ,' ARE COMPLETE WITH ',J ,
                        ' ITERATIONS AND A WORK DIFFERENCE OF' , RR2 ,' FT-LB/MIN' )
```

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PR6: PROCEDURE OPTIONS (MAIN)

          (SKIP(3), A(27) , F(6) , A(19) , F(3) , A(36), X(8), F(11,3),A(10) );
312       PUT EDIT ('.....VC.....ALPD.....W.....T1.....T2.....FC....',
                    'FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA')
                    (A(56),X(6), A(58) )                                      ;
313       PUT EDIT   (VC,ALPD,W,T1,T2,FC,FT,PFID,BED,WTL,WPD,THS,THMA,'...')
                    ( R(PMT01))                                               ;
314       PUT EDIT ('       LO         LBR        LBF        LAB        ET1        FT2'
                   ,'         E          WSD        NOSO       WPT        WKP      SFT2 '
                   ) ( A(60) , A(60)                                          );
315       PUT EDIT   (LO,LBE,LBF,LAB,ET1,ET2,E,WSD,NOSO,WPT,WKP,SFT2) (R(PMT03));
316       PUT EDIT ('      PSYD      GMD       DELD          RC       LT1R       LT2R',
                    '    SFT1       FS         SO         SS         WS      SSSO   ')
                    ( A(59) , X(1) , A(60)                                    );
317       PUT EDIT  (PSYD,GMD,DELD,RC,LT1R,LT2R,SFT1,FS,SO,SS,WS,SSSO)(R(PMT02));
318        PUT DATA ( TTHS, SOP, PSOP, ESSP, SSP, ESSSOP, SSSOP                  );
319        PUT DATA ( SFT2,ESFT2 ,CHID                                           );
320        SOT = SOT + SO                                                        ;
321        SST = SST + SS                                                        ;
322        IF SO < SON THEN SON = SO                                             ;
324        IF SS < SSN THEN SSN = SS                                             ;
326        IF SO > SOX THEN SOX = SO                                             ;
328        IF SS > SSX THEN SSX = SS                                             ;
330        SSSOS = SSSOS + SSSO                                                  ;
331        IF SSSO>SSSOX THEN SSSOX = SSSO ; IF SSSO<SSSON THEN SSSON = SSSO     ;
335        IF PSID < PSIDN THEN PSIDN = PSID                                     ;
337        IF PSID > PSIDX THEN PSIDX = PSID                                     ;
339        TT = TT+ 1                                                            ;
340        GO TO LBO                                                             ;
341       LBL:
           PUT EDIT (    '.' ) ( SKIP(1) , A(1) )                             ;
342        PUT EDIT ('.........................' ) ( PAGE,X(95), A(25) )         ;
343        SOA = (SOT-SON-SOX)/(TT - 2 )                                         ;
344        SSA = (SST-SSX-SSN)/(TT-2)                                            ;
345        SSSOA =(SSSOS-SSSON-SSSOX)/(TT-2)                                     ;
346        VSO = (SOX-SON)/SOA                                                   ;
347        VSS = (SSX-SSN)/SSA                                                   ;
348        VSSSO = ( SSSOX-SSSON)/SSSOA                                          ;
349        PUT DATA ( VSO , SOA , SON , SOX , VSS , SSA , SSN , SSX , TT       );
350        PUT DATA ( PSIDX , PSIDN , SSSOX , SSSON , SSSOA ,VSSSO             );
351        END  PR6                                                              ;
```

ITERATIONS ON TEST NUMBER 43089 ARE COMPLETE WITH 14 ITERATIONS AND A WORK DIFFERENCE OF -3.003 FT-LB/MIN

VC	ALPD	W	T1	T2	FC	FT	PFID	BED	WTL	WPD	THS	THMA
78.0	45.0	0.284	0.0201	0.0529	402.7	113.0	20.25	60.75	31262	20459	58	149...
LO	LBE	LBF	LAB	ET1	ET2	E	WSD	NOSO	WPT	WKF	SFT2	
0.0299	0.0475	0.0182	0.0476	1853	3198	2.24	0.00	1.00	20462	10802	42545	
PSYD	GMD	DELD	RC	LT1R	LT2R	SFT1	FS	SO	SS	NS	SSSO	
7.086	36.319	26.222	0.381	1.480	0.564	42632.4	42636.5	18298.5	22495.3	12589.2	1.2293	

TTHS= 1.14469E+02 SOP= 1.79754E+04 ESOP=-1.76576E+00 ESSP=-2.15706E+00 SSP= 2.20100E+04
ESSSOP=-3.98350E-01 SSSOP= 1.22445E+00; SFT2= 4.25451E+04 ESFT2=-2.04720E-01 CHID= 1.31952E+01;

ITERATIONS ON TEST NUMBER 43088 ARE COMPLETE WITH 21 ITERATIONS AND A WORK DIFFERENCE OF 9.453 FT-LB/MIN

VC	ALPD	W	T1	T2	FC	FT	PFID	BED	WTL	WPD	THS	THMA
78.0	40.0	0.284	0.0201	0.0659	450.8	147.8	16.25	58.23	35170	25538	68	151...
LO	LBE	LBF	LAB	ET1	ET2	E	WSD	NOSO	WPT	WKF	SFT2	
0.0344	0.0563	0.0234	0.0559	1601	1442	2.98	0.00	1.00	25529	9632	39017	
PSYD	GMD	DELD	RC	LT1R	LT2R	SFT1	FS	SO	SS	NS	SSSO	
10.886	31.651	22.966	0.306	1.703	0.521	41126.7	41131.3	16604.3	21316.8	10252.2	1.2838	

TTHS= 1.42881E+02 SOP= 1.65587E+04 ESOP=-2.74636E-01 ESSP=-1.18069E+00 SSP= 2.10651E+04
ESSSOP=-9.08575E-01 SSSOP= 1.27214E+00; SFT2= 3.90172E+04 ESFT2=-5.12932E+00 CHID= 1.36000E+01;

ITERATIONS ON TEST NUMBER 43087 ARE COMPLETE WITH 25 ITERATIONS AND A WORK DIFFERENCE OF -4.781 FT-LB/MIN

VC	ALPD	W	T1	T2	FC	FT	PFID	BED	WTL	WPD	THS	THMA
78.0	34.3	0.284	0.0201	0.0849	542.7	200.0	12.76	54.55	42338	33598	82	161...
LO	LBE	LBF	LAB	ET1	ET2	E	WSD	NOSO	WPT	WKF	SFT2	
0.0399	0.0684	0.0321	0.0660	1390	627	4.01	0.00	1.00	33603	8735	41072	
PSYD	GMD	DELD	RC	LT1R	LT2R	SFT1	FS	SO	SS	NS	SSSO	
16.461	27.422	18.576	0.237	1.979	0.470	41359.3	41358.5	15384.4	20938.9	8306.1	1.3607	

TTHS= 1.87980E+02 SOP= 1.54883E+04 ESOP= 6.75549E-01 ESSP= 3.35133E-01 SSP= 2.10051E+04
ESSSOP=-3.38147E-01 SSSOP= 1.35618E+00; SFT2= 4.10727E+04 ESFT2=-6.92879E-01 CHID= 1.20482E+01;

ITERATIONS ON TEST NUMBER 43086 ARE COMPLETE WITH 32 ITERATIONS AND A WORK DIFFERENCE OF -3.750 FT-LB/MIN

VC	ALPD	W	T1	T2	FC	FT	PFID	BED	WTL	WPD	THS	THMA
78.0	29.6	0.284	0.0201	0.0979	634.5	269.6	11.28	52.67	49498	40683	95	181...
LO	LBE	LBF	LAB	ET1	ET2	E	WSD	NOSO	WPT	WKF	SFT2	
0.0395	0.0752	0.0413	0.0698	1403	402	4.68	0.00	1.00	40686	8815	48988	
PSYD	GMD	DELD	RC	LT1R	LT2R	SFT1	FS	SO	SS	NS	SSSO	
21.992	27.764	17.359	0.206	1.958	0.403	48631.1	48630.1	15427.8	21937.7	8474.7	1.4219	

TTHS= 2.27616E+02 SOP= 1.54837E+04 ESOP= 3.62473E-01 ESSP= 9.82680E-01 SSP= 2.21533E+04
ESSSOP= 6.17960E-01 SSSOP= 1.43074E+00; SFT2= 4.89883E+04 ESFT2= 7.34515E-01 CHID= 1.03054E+01;

ITERATIONS ON TEST NUMBER 43085 ARE COMPLETE WITH 20 ITERATIONS AND A WORK DIFFERENCE OF -3.667 FT-LB/MIN

VC	ALPD	W	T1	T2	FC	FT	PFID	BED	WTL	WPD	THS	THMA
78.0	25.3	0.284	0.0201	0.1099	684.6	339.2	10.20	51.74	53406	44311	101	192...
LO	LBE	LBF	LAB	ET1	ET2	E	WSD	NOSO	WPT	WKF	SFT2	
0.0370	0.0817	0.0515	0.0730	1521	302	5.28	0.00	1.00	44315	8594	56757	
PSYD	GMD	DELD	RC	LT1R	LT2R	SFT1	FS	SO	SS	NS	SSSO	
27.090	30.010	18.438	0.183	1.834	0.336	56805.7	56819.1	14799.7	21642.5	8982.2	1.4623	

TTHS= 2.50717E+02 SOP= 1.47529E+04 ESOP=-3.16305E-01 ESSP= 7.29193E-01 SSP= 2.18004E+04
ESSSOP= 1.04878E+00 SSSOP= 1.47769E+00; SFT2= 5.67573E+04 ESFT2=-8.52548E-02 CHID= 1.24342E+01;

```
 ITERATIONS ON TEST NUMBER  43129 ARE COMPLETE WITH  26 ITERATIONS AND A WORK DIFFERENCE OF            -5.761 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    117.0      45.0    0.284   0.0201   0.0519    384.0     134.3     20.74     60.20     44939     29240        62       165...
      LO       LBE       LBP       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0321    0.0478    0.0160    0.0483      2901      6186      2.18      0.00      1.00     29246     15699     37885
     PSYD       GMD       DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
    5.222    35.541    29.302     0.388     1.591     0.618   37698.1   37697.9   18011.0   21779.0   12736.4    1.2092
TTHS= 1.09063E+02      SOP= 1.78415E+04      ESOP=-9.40830E-01      ESSP=-1.01127E+00      SSP= 2.15587E+04
RSSSOP=-7.11386E-02    SSSOP= 1.20834E+00;   SFT2= 3.78851E+04      RSFT2= 4.96138E-01     CHID= 1.38844E+01;

 ITERATIONS ON TEST NUMBER  43128 ARE COMPLETE WITH  15 ITERATIONS AND A WORK DIFFERENCE OF            -2.183 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    117.0      40.0    0.284   0.0201   0.0629    425.8     139.1     17.17     58.18     49824     35542        72       169...
      LO       LBE       LBP       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0353    0.0550    0.0209    0.0549      2679      2690      2.81      0.00      1.00     35545     14281     35613
     PSYD       GMD       DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
    8.964    32.176    25.674     0.320     1.750     0.561   37775.8   37779.8   16611.9   20774.3   11107.7    1.2505
TTHS= 1.32571E+02      SOP= 1.66004E+04      ESOP=-6.95563E-02      ESSP=-6.72404E-01      SSP= 2.06346E+04
RSSSOP=-6.03289E-01    SSSOP= 1.24301E+00;   SFT2= 3.56131E+04      RSFT2=-5.72498E+00     CHID= 1.45646E+01;

 ITERATIONS ON TEST NUMBER  43127 ARE COMPLETE WITH  24 ITERATIONS AND A WORK DIFFERENCE OF            -5.636 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    117.0      36.3    0.284   0.0201   0.0779    500.9     182.6     14.06     54.35     58616     45486        87       179...
      LO       LBE       LBP       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0405    0.0645    0.0269    0.0630      2389      1221      3.62      0.00      1.00     45491     13130     37325
     PSYD       GMD       DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
   13.749    28.234    20.936     0.258     2.007     0.519   37491.5   37491.0   15779.8   20670.0    9711.2    1.3103
TTHS= 1.69658E+02      SOP= 1.58508E+04      ESOP= 4.81933E-01      ESSP=-6.26284E-02      SSP= 2.06570E+04
RSSSOP=-5.41935E-01    SSSOP= 1.30321E+00;   SFT2= 3.73257E+04      RSFT2=-4.42183E-01     CHID= 1.24734E+01;

 ITERATIONS ON TEST NUMBER  43126 ARE COMPLETE WITH  12 ITERATIONS AND A WORK DIFFERENCE OF            -1.835 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    117.0      29.6    0.284   0.0201   0.0909    584.4     243.5     12.22     52.27     68386     55378       101       199...
      LO       LBE       LBP       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0406    0.0713    0.0356    0.0673      2349       725      4.30      0.00      1.00     55380     13007     43949
     PSYD       GMD       DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
   19.400    28.034    18.712     0.221     2.011     0.446   43278.1   43242.2   15626.1   21397.5    9519.7    1.3693
TTHS= 2.06556E+02      SOP= 1.56695E+04      ESOP= 2.77879E-01      ESSP= 1.21034E-02      SSP= 2.14001E+04
RSSSOP=-2.65067E-01    SSSOP= 1.36571E+00;   SFT2= 4.39995E+04      RSFT2= 1.66692E+00     CHID= 1.09472E+01;

 ITERATIONS ON TEST NUMBER  43125 ARE COMPLETE WITH  21 ITERATIONS AND A WORK DIFFERENCE OF            10.363 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    117.0      25.3    0.284   0.0201   0.1019    642.9     313.1     11.06     51.35     75225     62283       110       218...
      LO       LBE       LBP       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0372    0.0766    0.0457    0.0697      2534       530      4.86      0.00      1.00     62272     12941     52750
     PSYD       GMD       DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
   25.129    30.431    19.266     0.198     1.804     0.365   52583.0   52594.3   15282.2   21564.9   10020.0    1.4111
TTHS= 2.32310E+02      SOP= 1.52263E+04      ESOP=-3.65619E-01      ESSP=-4.11185E-01      SSP= 2.14762E+04
RSSSOP=-8.57539E-02    SSSOP= 1.41046E+00;   SFT2= 5.27501E+04      RSFT2= 1.17786E-01     CHID= 1.22789E+01;
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 ITERATIONS ON TEST NUMBER  43169 ARE COMPLETE WITH  21 ITERATIONS AND A WORK DIFFERENCE OF          -6.171 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....FC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    156.0      45.0    0.284   0.0201   0.0509    375.7     95.6     21.25     59.28    58616     38018        66       178...
      LO       LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0343    0.0480    0.0139    0.0487      3906     11157      2.13      0.00      1.00     38025     20598     34502
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
    3.690    34.515    32.168     0.396     1.700     0.673   34059.7   34059.6   18064.4   21616.6   12899.0    1.1966
TTHS= 1.06355E+02       SOP= 1.79605E+04       ESOP=-5.75132E-01       ESSP=-3.91192E-01       SSP= 2.15320E+04
ESSSOP= 1.84974E-01     SSSOP= 1.19485E+00;     SFT2= 3.45026E+04       ESFT2= 1.30027E+00      CHID= 1.33156E+01;

 ITERATIONS ON TEST NUMBER  43168 ARE COMPLETE WITH  24 ITERATIONS AND A WORK DIFFERENCE OF          -5.832 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....FC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    156.0      40.0    0.284   0.0201   0.0599    409.1     113.0     18.20     55.53    63827     45446        76       174...
      LO       LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0419    0.0549    0.0146    0.0556      3503      5273      2.63      0.00      1.00     45452     18380     31827
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
    5.539    29.243    28.638     0.336     2.033     0.684   29894.6   29894.3   16921.1   20727.6   11312.2    1.2249
TTHS= 1.27134E+02       SOP= 1.70237E+04       ESOP= 6.06329E-01       ESSP= 8.45471E-01       SSP= 2.09028E+04
ESSSOP= 2.37687E-01     SSSOP= 1.22786E+00;     SFT2= 3.18270E+04       ESFT2= 6.46392E+00      CHID= 1.21891E+01;

 ITERATIONS ON TEST NUMBER  43167 ARE COMPLETE WITH  21 ITERATIONS AND A WORK DIFFERENCE OF           1.156 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....FC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    156.0      34.3    0.284   0.0201   0.0719    467.5     165.2     15.38     53.78    72945     55431        88       189...
      LO       LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0420    0.0615    0.0217    0.0607      3635      2171      3.29      0.00      1.00     55430     17513     34055
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
   10.847    28.329    23.435     0.280     2.082     0.584   33371.9   33375.5   16205.2   20459.7   10953.2    1.2625
TTHS= 1.55066E+02       SOP= 1.62275E+04       ESOP= 1.37517E-01       ESSP= 4.29750E-01       SSP= 2.05476E+04
ESSSOP= 2.91797E-01     SSSOP= 1.26621E+00;     SFT2= 3.40557E+04       ESFT2= 2.04902E+00      CHID= 1.22472E+01;

 ITERATIONS ON TEST NUMBER  43166 ARE COMPLETE WITH  23 ITERATIONS AND A WORK DIFFERENCE OF          -12.062 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....FC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    156.0      29.6    0.284   0.0201   0.0839    551.0     226.1     13.34     51.96    85971     68369       105       215...
      LO       LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0406    0.0671    0.0307    0.0640      3541      1187      3.92      0.00      1.00     68381     17602     40322
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
   17.261    28.608    19.960     0.240     2.013     0.484   40471.5   40470.8   16224.0   21861.4   10792.5    1.3228
TTHS= 1.91258E+02       SOP= 1.61760E+04       ESOP=-2.95832E-01       ESSP=-4.58252E-01       SSP= 2.13631E+04
ESSSOP=-1.62932E-01     SSSOP= 1.32066E+00;     SFT2= 4.03229E+04       ESFT2=-3.67204E-01      CHID= 1.04906E+01;

 ITERATIONS ON TEST NUMBER  43165 ARE COMPLETE WITH  36 ITERATIONS AND A WORK DIFFERENCE OF          -7.687 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....FC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    156.0      25.3    0.284   0.0201   0.0959    601.1     295.7     11.80     51.57    93787     76556       113       235...
      LO       LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0359    0.0727    0.0424    0.0669      3865       826      4.54      0.00      1.00     76563     17231     48047
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        FS        SO        SS        NS      SSSO
   23.851    31.757    25.759     0.210     1.779     0.374   51245.2   51243.9   15481.1   21096.7   10994.6    1.3627
TTHS= 2.14160E+02       SOP= 1.53293E+04       ESOP=-9.80377E-01       ESSP=-1.35408E+00       SSP= 2.08110E+04
ESSSOP=-3.77413E-01     SSSOP= 1.35759E+00;     SFT2= 4.80477E+04       ESFT2=-8.23965E+00      CHID= 1.36390E+01;
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 ITERATIONS ON TEST NUMBER  43249 ARE COMPLETE WITH  22 ITERATIONS AND A WORK DIFFERENCE OF          -10.573 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BFD.....WTL.....WPD.....THS.....THRA
    235.0      45.0    0.284   0.0201   0.0499    367.7     86.9    21.79    58.32    86338    55833       71      201...
      LO       LBE      LBF      LAB      ET1      ET2       E       WSO      NOSO      WPT      WKF      SFT2
   0.0367    0.0482   0.0116   0.0492     5939    29726     2.07     0.00     1.00    55844    30505     29536
     PSYD      GMD      DELD       RC     LT1R     LT2R     SFT1       FS       SO       SS       WS     SSSO
    2.061    33.406   36.438    0.403    1.818    0.734  30693.6  30693.2  18115.1  21887.0  13063.8   1.1839
TTHS= 1.03684E+02      SOP= 1.80933E+04      RSOP=-1.20603E-01      RSSP= 1.72026E-01      SSP= 2.14839E+04
RSSSOP= 2.92967E-01    SSSOP= 1.18739E+00;   SFT2= 2.95365E+04     RSFT2=-3.76976E+00     CHID= 1.26970E+01;

 ITERATIONS ON TEST NUMBER  43248 ARE COMPLETE WITH  14 ITERATIONS AND A WORK DIFFERENCE OF           9.837 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BFD.....WTL.....WPD.....THS.....THRA
    235.0      40.0    0.284   0.0201   0.0569    401.7     104.3    19.35    54.67    94187    66044       82      200...
      LO       LBE      LBF      LAB      ET1      ET2       E       WSO      NOSO      WPT      WKF      SFT2
   0.0423    0.0535   0.0116   0.0548     5664    11949     2.46     0.00     1.00    66034    28143     28393
     PSYD      GMD      DELD       RC     LT1R     LT2R     SFT1       FS       SO       SS       WS     SSSO
    3.764    29.019   32.385    0.358    2.097    0.743  27982.7  27984.5  17551.8  21105.4  12271.3   1.2024
TTHS= 1.22645E+02      SOP= 1.75796E+04      RSOP= 1.58169E-01      RSSP= 7.35609E-01      SSP= 2.12607E+04
RSSSOP= 5.76505E-01    SSSOP= 1.20939E+00;   SFT2= 2.83934E+04     RSFT2= 1.46791E+00     CHID= 1.05528E+01;

 ITERATIONS ON TEST NUMBER  43247 ARE COMPLETE WITH  13 ITERATIONS AND A WORK DIFFERENCE OF          14.937 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BFD.....WTL.....WPD.....THS.....THRA
    235.0      38.3    0.284   0.0201   0.0668    450.8     147.8    16.69    52.48   105961    79295       95      212...
      LO       LBE      LBF      LAB      ET1      ET2       E       WSO      NOSO      WPT      WKF      SFT2
   0.0445    0.0592   0.0164   0.0590     5938     4480     3.01     0.00     1.00    79280    26666     30447
     PSYD      GMD      DELD       RC     LT1R     LT2R     SFT1       FS       SO       SS       WS     SSSO
    8.086    27.387   25.176    0.301    2.203    0.664  29662.3  29664.8  16941.7  20808.3  12004.7   1.2282
TTHS= 1.47252E+02      SOP= 1.69086E+04      RSOP=-1.95268E-01      RSSP= 6.60246E-01      SSP= 2.09465E+04
RSSSOP= 8.61176E-01    SSSOP= 1.23880E+00;   SFT2= 3.04470E+04     RSFT2= 2.64559E+00     CHID= 1.00348E+01;

 ITERATIONS ON TEST NUMBER  43246 ARE COMPLETE WITH  35 ITERATIONS AND A WORK DIFFERENCE OF          -12.312 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BFD.....WTL.....WPD.....THS.....THRA
    235.0      29.6    0.284   0.0201   0.0789    526.0     208.7    14.27    51.29   123621    97080      112      240...
      LO       LBE      LBF      LAB      ET1      ET2       E       WSO      NOSO      WPT      WKF      SFT2
   0.0421    0.0645   0.0261   0.0623     5836     2129     3.65     0.00     1.00    97093    26540     36193
     PSYD      GMD      DELD       RC     LT1R     LT2R     SFT1       FS       SO       SS       WS     SSSO
   14.997    28.230   20.756    0.255    2.085    0.533  36791.5  36791.0  16663.3  21416.6  11668.6   1.2852
TTHS= 1.80280E+02      SOP= 1.65696E+04      RSOP=-5.62517E-01      RSSP=-6.89096E-01      SSP= 2.12692E+04
RSSSOP=-1.26216E-01    SSSOP= 1.28362E+00;   SFT2= 3.61933E+04     RSFT2=-1.62585E+00     CHID= 9.68051E+00;

 ITERATIONS ON TEST NUMBER  43245 ARE COMPLETE WITH  21 ITERATIONS AND A WORK DIFFERENCE OF          15.750 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....PC....     FT.....PFID.....BFD.....WTL.....WPD.....THS.....THRA
    235.0      25.3    0.284   0.0201   0.0919    576.1     260.9    12.49    49.75   135395   110212      122      252...
      LO       LBE      LBF      LAB      ET1      ET2       E       WSO      NOSO      WPT      WKF      SFT2
   0.0423    0.0710   0.0344   0.0669     5918     1361     4.28     0.00     1.00   110196    25183     42168
     PSYD      GMD      DELD       RC     LT1R     LT2R     SFT1       FS       SO       SS       WS     SSSO
   19.899    28.515   19.969    0.221    2.096    0.465  39992.6  39998.6  15827.4  20937.6  11248.0   1.3228
TTHS= 2.04665E+02      SOP= 1.57415E+04      RSOP=-5.42349E-01      RSSP=-6.34884E-01      SSP= 2.08046E+04
RSSSOP=-9.30693E-02    SSSOP= 1.32164E+00;   SFT2= 4.21489E+04     RSFT2= 5.39296E+00     CHID= 1.11928E+01;
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 ITERATIONS ON TEST NUMBER  03329 ARE COMPLETE WITH  23 ITERATIONS AND A WORK DIFFERENCE OF            -7.500 FT-LB/MIN
.....VC......ALPD......W.......T1.........T2.........PC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    310.0      45.0    0.284    0.0201    0.0879     359.0     86.9     22.95     58.62   111305     70158        73       225...
      LO       LBR       LBP       LAB       ET1       ET2         F        WSO      WOSO      WPT       WKP      SFT2
   0.0348    0.0463    0.0115    0.0870      8991     41475      1.95       0.00      1.00    70165     41147     30265
     PSYD      GND      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
    2.066    35.226    36.696     0.420     1.726     0.726   31731.6   31731.5   18451.3   21541.5   14074.9    1.1674
TTHS= 9.87646E+01       SOP= 1.83734E+04       ESOP=-4.22182E-01       RSSP= 1.65124E-01       SSP= 2.15771E+04
RSSSOP= 5.89778E-01     SSSOP= 1.17436E+00;    SFT2= 3.02658E+04       RSFT2=-4.61921E+00      CHID= 1.30443E+01;

 ITERATIONS ON TEST NUMBER  03328 ARE COMPLETE WITH  17 ITERATIONS AND A WORK DIFFERENCE OF           -16.750 FT-LB/MIN
.....VC......ALPD......W.......T1.........T2.........PC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    310.0      40.0    0.284    0.0201    0.0539     392.0     95.6     20.65     53.78   121659     83866        85       220...
      LO       LBR       LBP       LAB       ET1       FT2         F        WSO      WOSO      WPT       WKP      SFT2
   0.0417    0.0512    0.0098    0.0520      7956     20311      2.29       0.00      1.00    83883     37792     27664
     PSYD      GND      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
    3.129    29.452    33.390     0.374     2.067     0.773   27378.2   27378.3   18163.0   21616.7   13113.9    1.1901
TTHS= 1.18062E+02       SOP= 1.81531E+04       ESOP=-5.47986E-02       RSSP= 3.77203E-01       SSP= 2.16982E+04
RSSSOP= 4.32225E-01     SSSOP= 1.19529E+00;    SFT2= 2.76691E+04       RSFT2= 1.04429E+00      CHID= 9.21566E+00;

 ITERATIONS ON TEST NUMBER  03327 ARE COMPLETE WITH  15 ITERATIONS AND A WORK DIFFERENCE OF            -3.937 FT-LB/MIN
.....VC......ALPD......W.......T1.........T2.........PC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    310.0      34.3    0.284    0.0201    0.0629     434.1     110.4     17.91     51.04   134601     99555        97       226...
      LO       LBR       LBP       LAB       ET1       PT2         F        WSD      WOSO      WPT       WKP      SFT2
   0.0455    0.0568    0.0127    0.0570      9139      7592      2.79       0.00      1.00    99559     35046     28451
     PSYD      GND      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
    6.564    26.699    25.078     0.320     2.252     0.722   27183.7   27185.5   17376.0   21055.7   12559.5    1.2117
TTHS= 1.40148E+02       SOP= 1.74155E+04       ESOP= 2.27459E-01       RSSP= 9.08857E-01       SSP= 2.12471E+04
RSSSOP= 6.79817E-01     SSSOP= 1.22301E+00;    SFT2= 2.84516E+04       RSFT2= 8.66430E+00      CHID= 8.54758E+00;
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 ITERATIONS ON TEST NUMBER  03326 ARE COMPLETE WITH  26 ITERATIONS AND A WORK DIFFERENCE OF           -15.375 FT-LB/MIN
.....VC......ALPD......W.......T1.........T2.........PC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    310.0      39.6    0.284    0.0201    0.0729     492.6     191.3     15.56     50.98   152721    117546       111       256...
      LO       LBR       LBP       LAB       ET1       PT2         F        WSD      WOSO      WPT       WKP      SFT2
   0.0411    0.0604    0.0226    0.0587      9814      3454      3.33       0.00      1.00   117562     35174     33160
     PSYD      GND      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
   13.593    29.034    21.567     0.276     2.035     0.563   34994.0   34993.6   17044.8   21294.5   12694.8    1.2496
TTHS= 1.65475E+02       SOP= 1.69030E+04       ESOP=-8.09135E-01       RSSP=-8.74948E-01       SSP= 2.11082E+04
RSSSOP=-6.63961E-02     SSSOP= 1.24878E+00;    SFT2= 3.31602E+04       RSFT2=-5.24021E+00      CHID= 9.86228E+00;

 ITERATIONS ON TEST NUMBER  03325 ARE COMPLETE WITH  30 ITERATIONS AND A WORK DIFFERENCE OF           -24.312 FT-LB/MIN
.....VC......ALPD......W.......T1.........T2.........PC....      FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    310.0      25.3    0.284    0.0201    0.0949     551.0     234.8     13.44     48.46   170940    137834       126       266...
      LO       LBR       LBP       LAB       ET1       PT2         F        WSD      WOSO      WPT       WKP      SFT2
   0.0441    0.0675    0.0298    0.0643      8170      2079      3.97       0.00      1.00   137829     33036     37908
     PSYD      GND      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
   17.797    27.365    18.977     0.237     2.185     0.519   35642.3   35641.7   16283.6   21102.1   11787.9    1.2959
TTHS= 1.93992E+02       SOP= 1.62769E+04       ESOP=-4.11648E-02       RSSP=-4.46959E-01       SSP= 2.10078E+04
RSSSOP=-8.06000E-01     SSSOP= 1.29065E+00;    SFT2= 3.79983E+04       RSFT2= 6.35747E+00      CHID= 9.53679E+00;
```

```
 ITERATIONS ON TEST NUMBER  43489 ARE COMPLETE WITH  15 ITERATIONS AND A WORK DIFFERENCE OF            -16.500 FT-LB/MIN
.....VC......ALPD.....W......T1.......T2.......PC....      PT......PFID.....BRD.....WTL.....WPD.....THS.....THMA
    470.0      45.0    0.284    0.0201    0.0459    350.6      78.2     24.24     57.58    164828    102220        76       267...
      LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0325    0.0436    0.0112    0.0480     13977     44672      1.84      0.00      1.00    102236     62608     33214
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
    3.247    36.536    32.296     0.439     1.612     0.708   32672.9   32674.9   18743.2   21951.2   14413.6    1.1711
TTHS= 9.49125E+01       SOP= 1.87841E+04       ESOP= 2.17869E-01       ESSP=-5.20826E-01       SSP= 2.18369E+04
ESSSOP=-7.37105E-01     SSSOP= 1.16252E+00;     SFT2= 3.32145E+04       ESFT2= 1.65759E+00      CHID= 1.28832E+01;

 ITERATIONS ON TEST NUMBER  43488 ARE COMPLETE WITH  21 ITERATIONS AND A WORK DIFFERENCE OF            -21.000 FT-LB/MIN
.....VC......ALPD.....W......T1.......T2.......PC....      PT......PFID.....BRD.....WTL.....WPD.....THS.....THMA
    470.0      40.0    0.284    0.0201    0.0519    384.0      86.9     21.62     52.84    180526    123221        90       256...
      LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0404    0.0491    0.0090    0.0898     12237     29915      2.18      0.00      1.00    123242     57305     27579
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
    3.451    29.917    30.870     0.388     2.303     0.778   27209.0   27208.8   18415.5   21923.5   13375.0    1.1904
TTHS= 1.14411E+02       SOP= 1.85146E+04       ESOP= 5.38353E-01       ESSP=-2.20545E-01       SSP= 2.18752E+04
ESSSOP=-7.54850E-01     SSSOP= 1.18150E+00;     SFT2= 2.75797E+04       ESFT2= 1.36235E+00      CHID= 9.75905E+00;

 ITERATIONS ON TEST NUMBER  43487 ARE COMPLETE WITH  24 ITERATIONS AND A WORK DIFFERENCE OF            -21.812 FT-LB/MIN
.....VC......ALPD.....W......T1.......T2.......PC....      PT......PFID.....BRD.....WTL.....WPD.....THS.....THMA
    470.0      34.3    0.284    0.0201    0.0609    417.4     121.7     18.58     50.58    196224    143932       102       255...
      LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0456    0.0555    0.0113    0.0557     12858     13194      2.69      0.00      1.00    143953     52292     26018
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
    5.929    26.741    25.807     0.331     2.248     0.704   25951.1   25950.9   17277.5   20763.7   12720.1    1.2018
TTHS= 1.33642E+02       SOP= 1.74450E+04       ESOP= 9.72389E-01       ESSP= 9.01981E-01       SSP= 2.09510E+04
ESSSOP=-6.97513E-02     SSSOP= 1.20097E+00;     SFT2= 2.60183E+04       ESFT2= 2.58779E-01      CHID= 9.10499E+00;

 ITERATIONS ON TEST NUMBER  43486 ARE COMPLETE WITH   5 ITERATIONS AND A WORK DIFFERENCE OF            -3.375 FT-LB/MIN
.....VC......ALPD.....W......T1.......T2.......PC....      PT......PFID.....BRD.....WTL.....WPD.....THS.....THMA
    470.0      29.6    0.284    0.0201    0.0689    450.8     173.9     16.56     50.75    211922    160424       111       277...
      LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0811    0.0581    0.0198    0.0569     15239      6291      3.12      0.00      1.00    160427     51498     29200
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
   12.000    29.368    22.826     0.292     2.037     0.596   31831.4   31910.8   16649.2   20253.0   13009.2    1.2164
TTHS= 1.48955E+02       SOP= 1.66177E+04       ESOP=-1.89127E-01       ESSP=-3.65782E-01       SSP= 2.01789E+04
ESSSOP=-1.77022E-01     SSSOP= 1.21430E+00;     SFT2= 2.92004E+04       ESFT2=-8.26540E+00      CHID= 1.21807E+01;

 ITERATIONS ON TEST NUMBER  43084 ARE COMPLETE WITH  24 ITERATIONS AND A WORK DIFFERENCE OF            -3.062 FT-LB/MIN
.....VC......ALPD.....W......T1.......T2.......PC....      PT......PFID.....BRD.....WTL.....WPD.....THS.....THMA
     78.0      19.5    0.284    0.0201    0.1159    726.4     400.1      9.91     47.42     56663     48367       108       199...
      LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKP      SFT2
   0.0359    0.0839    0.0570    0.0727      1831       236      5.56      0.00      1.00     48371      8295     66018
     PSYD       GMD      DELD        RC      LT1R      LT2R      SFT1        PS        SO        SS        NS      SSSO
   32.612    32.185    18.981     0.174     1.779     0.309   59598.4   59616.2   18992.5   21987.4   10725.4    1.4665
TTHS= 2.70612E+02       SOP= 1.88634E+04       ESOP=-8.61338E-01       ESSP= 1.98102E+00       SSP= 2.24010E+04
ESSSOP= 2.76616E+00     SSSOP= 1.50712E+00;     SFT2= 6.60188E+04       ESFT2= 1.07660E+01      CHID= 1.23903E+01;
```

```
 ITERATIONS ON TEST NUMBER  43124 ARE COMPLETE WITH  41 ITERATIONS AND A WORK DIFFERENCE OF            -12.812 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....FC....      PT.....PFID.....BFD.....WTL.....WPD.....THS.....THMA
    117.0      18.5    0.284   0.0201   0.1099     684.6     382.7     10.47     47.77     80109     67628       118       233...
      LO        LBE       LBF       LAB       ET1       ET2         F       WSD      NOSO       WPT       WKF      SFT2
   0.0321    0.0795    0.0553    0.0693      3061       411      5.26      0.00      1.00     67641     12481     64183
    PSYD       GMD      DELD        RC      LT1F      LT2F      SFT1        PS        SO        SS        NS      SSSO
    32.977    34.382    20.016     0.183     1.592     0.292  63155.3   63153.0   15092.8   21648.7   11430.7    1.4343
TTHS= 2.52247E+02       SOP= 1.49864E+04       FSOP=-7.05061E-01       BSSP=-4.21954E-01       SSP= 2.15673E+04
BSSSOP= 2.85098E-01     SSSOP= 1.43845E+00;    SFT2= 6.41835E+04       BSFT2= 1.30727E+00      CHID= 1.42571E+01;

 ITERATIONS ON TEST NUMBER  43164 ARE COMPLETE WITH  29 ITERATIONS AND A WORK DIFFERENCE OF            10.000 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....FC....      PT.....PFID.....BFD.....WTL.....WPD.....THS.....THMA
    156.0      18.5    0.284   0.0201   0.1049     642.9     356.6     10.99     47.59    100300     84007       122       248...
      LO        LBE       LBF       LAB       ET1       ET2         F       WSD      NOSO       WPT       WKF      SFT2
   0.0318    0.0762    0.0520    0.0673      4460       608      5.01      0.00      1.00     83997     16293     58660
    PSYD       GMD      DELD        RC      LT1F      LT2F      SFT1        PS        SO        SS        NS      SSSO
    31.973    34.821    20.543     0.192     1.576     0.303  59915.3   59832.5   15061.7   21027.1   11789.1    1.3960
TTHS= 2.35004E+02       SOP= 1.40499E+04       FSOP=-7.88792E-01       BSSP=-1.36270E+00       SSP= 2.07406E+04
BSSSOP=-6.18562E-01     SSSOP= 1.38742E+00;    SFT2= 5.86605E+04       BSFT2=-1.93064E+00      CHID= 1.55835E+01;

 ITERATIONS ON TEST NUMBER  43244 ARE COMPLETE WITH  20 ITERATIONS AND A WORK DIFFERENCE OF             2.687 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....FC....      PT.....PFID.....BFD.....WTL.....WPD.....THS.....THMA
    235.0      18.5    0.284   0.0201   0.1009     617.8     313.1     11.44     45.44    185206    122003       133       258...
      LO        LBE       LBF       LAB       ET1       ET2         F       WSD      NOSO       WPT       WKF      SFT2
   0.0414    0.0751    0.0425    0.0682      6512       896      4.81      0.00      1.00    122001     23202     51121
    PSYD       GMD      DELD        RC      LT1F      LT2F      SFT1        PS        SO        SS        NS      SSSO
    26.851    29.531    18.460     0.200     2.051     0.410  41786.0   41795.0   15180.6   20640.1   11492.7    1.3596
TTHS= 2.26563E+02       SOP= 1.51983E+04       FSOP= 1.16976E-01       BSSP=-3.51024E-01       SSP= 2.05677E+04
BSSSOP=-4.66864E-01     SSSOP= 1.35328E+00;    SFT2= 5.11214E+04       BSFT2= 2.23407E+01      CHID= 1.24911E+01;

 ITERATIONS ON TEST NUMBER  43324 ARE COMPLETE WITH  32 ITERATIONS AND A WORK DIFFERENCE OF            -21.912 FT-LB/MIN
.....VC.....ALPD.....W.....T1.....T2.....FC....      PT.....PFID.....BFD.....WTL.....WPD.....THS.....THMA
    310.0      18.5    0.284   0.0201   0.0959     592.8     287.0     12.06     44.40    183783    153715       137       270...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
   0.0440    0.0724    0.0372    0.0667      8898      1298      4.56      0.00      1.00    153737     30067     95789
    PSYD       GMD      DELD        RC      LT1F      LT2F      SFT1        PS        SO        SS        NS      SSSO
    24.597    27.944    17.319     0.219     2.189     0.458  36726.4   36725.6   15416.2   20533.7   11748.9    1.3319
TTHS= 2.16392E+02       SOP= 1.55081E+04       FSOP= 5.97508E-01       BSSP=-1.70641E-01       SSP= 2.04987E+04
BSSSOP=-7.63607E-01     SSSOP= 1.32178E+00;    SFT2= 4.57893E+04       BSFT2= 2.06769E+01      CHID= 1.12609E+01;
.
```

```
VSO= 2.37912E-01        SOA= 1.65755E+04       SON= 1.47997E+04       SOX= 1.87432E+04       .......................
SSA= 2.12556E+04        SSN= 2.02530E+04       SSX= 2.24953E+04       TT=        30;         VSS= 1.05491E-01
PSIDN= 2.06123E+00      SSSOX= 1.46655E+00     SSSON= 1.16747E+00     SSSOA= 1.28595E+00      PSIDX= 3.29778E+01
                                                                                              VSSSO= 2.32575E-01;
```

```
PR4: PROCEDURE OPTIONS (MAIN)

  1             PR4: PROCEDURE OPTIONS (MAIN)                                    ;
  2              CALL MPR                                                        ;
  3             MPR: PROCEDURE                                                   ;
  4              DCL C(2) , D(2)  , G(2)  , AR(7,30) , B(30)                     ;
  5              DCL Z(2) , GT(2)                                                ;
  6              DCL R(7,30)                                                     ;
  7              PT1 = 400 ;  TTHS = 100 ;
  9              KLL = 0                                                         ;
 10              DO VC = 480 , 320 , 240 , 160 , 120 , 80 ;
 11              PUT EDIT ('.') ( PAGE , A(1) ) ;
 12              DO ALPD = 45 , 40 , 35 , 30 , 25 , 20                           ;
 13              LSTTM:
                 SS = 22500 ;
 14              IF ALPD = 45 THEN DO ; PSN=2 ; PSX=7 ; PSS=1 ; DLN=26 ; DLX=36;DLS=2 ;
 22               SRN = 1.16 ; SRX = 1.23 ; /* 45 DEGREES */
 24               SR = 1.17 ; SO = 18800 ; E = 1.9 ;                             END ;
 28              IF ALPD = 40 THEN DO ; PSN=3 ; PSX=11; PSS=1 ; DLN=23 ; DLX=33;DLS=2 ;
 36               SRN = 1.19 ; SRX = 1.29 ;  /* 40 DEGREES */
 38               SR = 1.19 ; SO = 18500 ; E = 2.2 ;                             END ;
 42              IF ALPD=35 THEN DO ; PSN=6 ; PSX = 16;PSS=2 ; DLN=17 ; DLX=23;DLS=1.5;
 50               SRN = 1.20 ; SRX = 1.36 ; /* 35 DEGREES */
 52               SR = 1.70 ; SO = 17200  ; E = 2.7 ;                            END ;
 56              IF ALPD = 30 THEN DO ; PSN=12; PSX=22; PSS=2 ; DLN=17 ; DLX=23;DLS=1 ;
 60               SRN = 1.21 ; SRX = 1.37 ; /* 30 DEGREES */
 66               SR = 1.22 ; SO = 17005 ; E = 3.2 ;                             END ;
 70              IF ALPD=25 THEN DO ; PSN=18;PSX=28;DLN=17;DLX=22;DLS=1 ;  PSS=2      ;
 78               SRN = 1.28 ; SRX = 1.47 ; /* 25 DEGREES */
 80               SR  = 1.29 ; SO = 16250 ; E = 4.0 ;                            END ;
 84              IF ALPD = 20 THEN DO ; SRN = 1.27 ; SRX=1.5 ; SR = 1.4 ; PSX=32;
 90                             DLN = 13 ; SO = 16000 ;                          END ;
 93              PSNH = PSN ; PSXH = PSX ; PSSH = PSS ; DLNH=DLN;DLXH=DLX;DLSH=DLS    ;
 99              KL = 0 ;
100              LLL = 0  ;
101              D(*) = 0.1000001 ;
102              C(1) = (PSN+PSX)/2 ; C(2) = (DLN+DLX)/2  ;
104              LABEL:
                 SPSO = 10**75                                                   ;
105              DEL1 = 200.0 ; DEL2 = 0.001 ;
107              DEL1 = 12000 ;
109              HIJ = 20 ;
109             CALL TAYLOR (NN,MM,C,D,G,HIJ,DEL1,DEL2,XX,SPSQ,FF,PXTI,B,B,VC,ALPD,SR,
                              F,PT1,TTHS,SO,SS                                    );
110              CALL STS ;
111                STS: PROCEDURE                ;
112              IF F > 6.0 THEN E = 6.0 ; IF F < 1.6 THEN E = 1.6 ;
116              IF TTHS > 300 THEN TTHS = 300 ; IF TTHS < 80 THEN TTHS = 80 ;
120              IF PT1 > 50000 THEN PT1 = 50000 ; IF PT1 < 300 THEN PT1 = 300 ;
124              SKO = 1.12033 ; GK = 6.08377 ; T = TTHS/1000 ; AA = -.0123976 ;
129              BB = 0.340393 ;   CC = -0.16177 ;
130              SSSOP = SKO*(GK**T)*(F**(AA+BB*T))*(PT1**(CC*T))                ;
131              SSK = 15830 ; GSK = 8305.47 ; AAS = -0.492552 ; BBS = -2.16237 ;
135              CCS = -0.120091 ;
136              SSP = SSK*(GSK**T)*(F**(AAS+BBS*T))*(PT1**(CCS*T))              ;
```

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PR4: PROCEDURE OPTIONS (MAIN)

137               IF SSP > 22200 THEN SSP = 22200 ; IF SSP< 20100 THEN SSP = 20400 ;
141               IF SSSOP < SBN THEN SSSOP = SBN ; IF SSSOP > SBX THEN SSSOP = SBX    ;
145               SOP = SSP/SSSOP ;
146               END STS ;
147               SSSO = SR ;
148               KL = KL + 1 ;
149               IF KL > 20 THEN GO TO THE_END ;
151              IF KK=-1 | ABS(SO-SOP)>300 | SSSO>(SSSOP+0.002) | SSSO<(SSSOP-0.001)
152                                                                    THEN DO   ;
153               SSSO = SSSOP ; SR = SSSOP ; SO = SOP ; SS = SSP ;
157               JKJ = 0 ;
158               IF KK = -1 THEN DO ; SOH = 10**75 ;
161              STP:
162               DO Z(1) = PSN TO PSX BY PSS      ;  DO Z(2) = DLN TO DLX BY DLS      ;
163               LK = -3 ;
164               CALL FNCTN (Z,G,AR,R,LK ,VC,ALFD,SR,E , ET1,THS,SO,SS                ) ;
165               SQM = SQM(G(*)**2) ;
166               IF SQM < SOH THEN DO ; SQH = SQM;C(*) = Z(*); CALL STS ;          END ;
172               END ; END ;
174               PSN = C(1) - PSS ; PSX = C(1) + PSS ; PSS = PSS/4 ;
177               DLN = C(2) - DLS ; DLX = C(2) + DLS ; DLS = DLS/4 ;
180               JKJ = JKJ + 1 ;
181               IF JKJ < 2 THEN GO TO STP ;
183               DLS=DLSH ; DLX=DLXH ; DLN=DLNH ; PSS=PSSH ; PSX=PSXH ; PSN = PSNH    ;
189               CALL STS ;
190               END ;
191                 LK = 0 ;
192               GO TO LABEL ;
193              END ;
194              THE_END:
                  LK = 3          ;
195               CALL FNCTN (C,G,AR,R,LK ,VC,ALFD,SR,E , ET1,THS,SO,SS                ) ;
196               END ; END ;  /* DO RANGE OF OSPREDS & FEEDS  */
198              END MPR                                                               ;
                  /*                                                                 */
                  /*                                                                 */
199              TAYLOR: PROCEDURE (JJJ,LLL,X,H,F,ITMAX,EPS1,EPS2,DER,S,KFNN,FXIT,AR,BH,
                      VEL,ALF,SRH,FTT,ET1TT,TTHSTT,SOTT,SSTT                         ) ;
200               DCL X(2) , F(2) , H(2) , FP(2) , FM(2) , B(2) , DX(2) , DFDX(2,2) ,
                       AA(2,2) , AR(7,30) , BH(2)                                    ;
201                  DCL Z BINARY FIXED                                              ;
202                ON ERROR GO TO LB    ;
204               SR = SRH ;
205               AL = ALF                                                          ;
206                  HS = S                                                         ;
207                     N = 2   ;    M = 2      ;
209                  JK = 0                                                         ;
210                  Z = 0                                                          ;
211                  KFNN = 0                                                       ;
212              ITERATION:
                     Z = Z + 1                                                      ;
213                  IF Z > ITMAX THEN DO                                           ;
215                     KFNN = 1
```

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PR4: PROCEDURE OPTIONS (MAIN)

216                    GO TO ENDE                                                ;
217                 END  /* IF Z > ITMAX    */                                  ;
218                 L = 0                                                       ;
219                 HL = 1.0                                                    ;
220              DAMP:
                    L = L + 1                                                  ;
221               IF KENN = 0 & L > 16 THEN DO ;
223               KENN = 3 ; HL = 1.0 ; L = 0 ; DX(*) = -DX(*) ;
227               L = 16 ;   DX(*) = 0 ;  /* THIS CARD PREVENTS 15 EQUAL STEPS  */
229               END ;
230               IF KENN = 3 & L = 16 THEN DO ; KENN=-1 ; X(*) = X(*)-DX(*);GOTO ENDE ;
235               END ;
236              LBI:
237               IF X(1) < 1.0 THEN DO ; KENN=-1 ; GOTO ENDE ; END ;
241               CALL FNCTN ( X , F , AP , BH , JK , VEL , AL , SR ,ETT,ET1TT,THSTT,
                              SOTT,SSTT                                          );
242                  N = 2     ;    M = 2                                       ;
244                  HF = 0                                                     ;
245                  DO I = 1 TO M  ; HF = HF + F(I)*F(I)   ;  END              ;
249                  IF HF > (HS*(1.0 - 0.2*HL)) THEN DO                        ;
250               IF KENN = 0 THEN HL = HL/2 ; ELSE HL = 1/15 ;
253                     DO K = 1 TO N ; X(K) = X(K) + HL*DX(K) ; END            ;
256                   GO TO DAMP                                               ;
257                  END   /* IF HF > (HS*(1.0-0.2*HL))   */                   ;
258                  HS = HF                                                    ;
259                  IF HS < EPS1 THEN GO TO ENDE                               ;
261               IF HS < 3000 THEN H(*) = 0.01 ;  IF HS < 300 THEN H(*) = 0.001 ;
265                  M = 2     ;    N = 2                                       ;
267                DO I = 1 TO N    ; HF = H(I) ;  HZ = 2.0*HF                  ;
270              LB0:
                    X(I) = X(I) + HF                                           ;
271               CALL FNCTN ( X , FF, AR , BH , JK , VEL , AL , SR ,ETT,ET1TT,THSTT,
                              SOTT,SSTT                                          );
272                  X(I) = X(I) - HF  ;
273                  DO K = 1 TO M ; DFDX(K,I) = (FF(K)-F(K))/HF     ; END      ;
276               END                                 /* I = 1 TO N */         ;
277              LBK:
278                  M = 2     ;    N = 2                                       ;
279                IF M = N THEN DO ; CALL GAUSS (N,DFDX,F,DX,EXIT)   ;  END    ;
283               ELSE DO                                                      ;
284              LBL:
285                  DO I = 1 TO N   ;                                         ;
286                     HF = 0                                                 ;
287                     DO K = 1 TO M ; HF =  HF + (DFDX(K,I))*F(K)   ; END    ;
290                     B(I) = HF                                              ;
291                     DO K = I TO N                                          ;
292                        HF = 0                                              ;
293                         DO J = 1 TO M ; HF = HF + (DFDX(J,I))*(DFDX(J,K)) ; END ;
296                         AA(I,K) = HF                                       ;
297                         AA(K,I) = HF                                       ;
298                     END  /* DO K = I TO N */                               ;
299                  END    /* DO I = 1 TO N    */                            ;
300                CALL GAUSS ( N , AA , B , DX , EXIT )                       ;
```

```
PR4: PROCEDURE OPTIONS (MAIN)

301               END /* ELSE DO FOR IF M = N */                                    ;
302                  BZ = 0                                                        ;
303                  BP = 0                                                        ;
304                  DO I = 1 TO N                                                 ;
305               IF (X(I) - DX(I) ) < 1.0 THEN DX(I) = X(I) - 1.0 ;
307               IF (X(I)-DX(I)) > 40 THEN DX(I) = X(I) - 40 ;
309                     X(I) = X(I) - DX(I)                                       ;
310            LBM:
                        BZ = BZ + ABS(X(I))                                      ;
311                     BP = BP + ABS(DX(I))                                     ;
312                  END  /* DO I = 1 TO N     */                                ;
313                  IF BP >= EPS2*BZ THEN GO TO ITERATION                         ;
315            ENDR:
316               IF KEWN = 0 THEN JK = 2 ; ELSE JK = KEWN ;
318               CALL FNCTN ( X , F , AR , DH , JK , VEL , AL , SR ,ETT,ET1TT,THSTT,
                           SOTT,SSTT                                              );
319            LR:
                  S = 0                                                          ;
320               ITMAX = 7                                                      ;
321               DO I = 1 TO M     ; S = S + F(I)*F(I)  ;  END                  ;
324              RETURN                                                          ;
325               END TAYLOR                                                     ;
                  /*                                                           */
                  /*                                                           */
                  /*                                                           */
326            GAUSS: PROCEDURE ( MM , AR, B , X , EXIT )                        ;
327               DCL X(7) , AR(7,30)                                            ;
328               DCL A(4) , B(2) , BH(2) ,AH(4)                                 ;
329               ON ERROR GO TO LL4          ;
331               NN = 0                                                         ;
332            L0:
333               DO L = 1 TO MM  ; DO M = 1 TO MM ; NN = NN+1 ; A(NN)= AR(M,L);END;END;
338            L1:
                     N = MM                                                      ;
339            L2:
340               BH(1) = B(1) ; BH(2) = B(2)                                    ;
341               TOL = 0.0001                                                   ;
342               KS = 0                                                         ;
343               JJ = -N                                                        ;
344               DO J = 1 TO N                                                  ;
345                  JY = J+1                                                    ;
346                  JJ = JJ+N+1                                                 ;
347            L3:
                     BIGA = 0.0                                                  ;
348                  IT = JJ-J                                                   ;
                     /* SEARCH FOR MAX COEFFICIENT IN COLUMN          */
349                  DO I = J TO N                                               ;
350                    IJ = IT+I                                                 ;
351                    IF ( ABS(BIGA) - ABS(A(IJ)) ) < 0.0 THEN DO               ;
353            L4:
                        BIGA = A(IJ)                                             ;
354                     IMAX = I                                                 ;
355                   END  /* (ABS(BIGA) - ABS(A(IJ))) < 0.0                  */ ;
```

```
PR4: PROCEDURE OPTIONS (MAIN)

356                 END  /* I = J TO N */                                    ;
                    /* TEST FOR PIVOT LESS THAN TO L                  */
                    /* INTERCHANGE ROWS IF NECESSARY  */
357               L5:
                    I1 = J+N*(J-2)                                          ;
358                 IT = IMAX-J                                             ;
359                 DO K = J TO N                                           ;
360                   I1 = I1+N                                             ;
361                   I2 = I1 + IT                                          ;
362               L6:
                    SAVE = A(I1)                                            ;
363               L7:
                      A(I1) = A(I2)                                         ;
364                   A(I2) = SAVE                                          ;
                      /*  DIVIDE EQUATION BY LEADING COEFFICIENT  */
365                   A(I1) = A(I1)/BIGA                                    ;
366                 END  /* IF ( ABS(DO K = J TO N           */             ;
367                 SAVE = B(IMAX)                                          ;
368               L8:
369                BH(1) = B(1) ; BH(2) = B(2)                             ;
370                 B(IMAX) = B(J)                                          ;
371                 B(J) = SAVE/BIGA                                        ;
372               L9:
373                BH(1) = B(1) ; BH(2) = B(2)                             ;
374                 IF J = N THEN GO TO BKSOL                               ;
                    /* ELIMINATE NEXT VARIABLE                    */
376                 IQS = N*(J-1)                                           ;
377                 DO IX = JY TO N                                         ;
378                   IXJ = IQS + IX                                        ;
379                   IT = J - IX                                           ;
380                   DO JX = JY TO N                                       ;
381                     IXJX = N*(JX-1) + IX                                ;
382                     JJX = IXJX + IT                                     ;
383                     A(IXJX) = A(IXJX) - (A(IXJ))*A(JJX)                 ;
384                   END   /* DO JX = JY TO N       */                     ;
385                   B(IX) = B(IX) - (B(J))*(A(IXJ))                       ;
386                END   /* DO IX = JY TO N                  */           ;
387                END   /* J = 1 TO N              */                     ;
388               BKSOL:     /* BACK SOLUTION         */
                   NY = N-1                                                 ;
389                IT = N*N                                                ;
390                DO J = 1 TO NY                                          ;
391                  IA = IT - J                                           ;
392                  IB = N - J                                            ;
393                  IC = N                                                ;
394                  DO K = 1 TO J                                         ;
395                    B(IB) = B(IB) - (A(IA))*(B(IC))                     ;
396                    IA = IA - N                                         ;
397                    IC = IC - 1                                         ;
398                  END  /* DO K = 1 TO J         */                      ;
399                END   /* DO J = 1 TO NY     */                         ;
400               LL8:
401                DO LL = 1 TO N ; X(LL) = B(LL)     ;   END              ;
```

```
PR4: PROCEDURE OPTIONS (MAIN)

403                RETURN                                                          ;
404               END GAUSS                                                        ;
                   /*                                                           */
                   /*                                                           */
                   /*                                                           */
405               FNCTN: PROCEDURE ( C , G , BB , FL , TST , VEL , ALP , SSSOB ,
                                     ET,ET1T,TTHST,SOT,SST                        );
406                 DCL C(2) , G(2) , BB(7,30) , FL(30)                           ;
407                 DECLARE ( HH,GG,TST,I                          ) BINARY FIXED (31,0);
408                 DECLARE (     K , LAB , LBB , LBF , LO , LT1R , LT2R , NOSO , NS    )
                                                                        DECIMAL    ;
409                 DECLARE GR(55) , DR0(35) , DR1(55) , CH(55) , R0(25) , R1(25)  ;
410                   DECLARE PS(201) , DL(101) , TS(101)                         ;
411                 ON ERROR GO TO L2 ;
412                 FMT01:
                    FORMAT (SKIP, 2 F(9,1),F(9,3),2 F(9,4),2 F(9,1),2 F(9,2),4 F(9),A(3));
414               FMT02: FORMAT (3 F(10,2), 3 F(10,3) , 5 F(10,1) , F(10,4)       );
415               FMT03: FORMAT ( 4 F(10,4) , 2 F(10,2) , 2 F(10,2) , 4 F(10,0)   );
416                 SSSO = SSSOR ;
417                    PSID = C(1)     ;   DELD = C(2)                            ;
419                 DL(L) = DELD                                                  ;
420                 VC = VEL ; ALFD = ALP                                         ;
422                 SII = 15000                                                   ;
423                 PI  = 3.14159265536                                ;
424                 DTR = PI/180.0                                     ;
425                 RTD = 180/PI                                       ;
426                 P   = 0.0975                                       ;
427                 K   = 10.81                                        ;
428                 CP  = 0.243                                        ;
429                 W   = 0.280                                        ;
430                 T1  = 0.0202                                       ;
431                 NOSO = 1.00                                                   ;
432               LO:
                    I = 43000 + VC + ALFD/5                                       ;
433                    J = 1                                                      ;
434               L3:
                    III = III + 1                                                 ;
435                 PSIR= PSID*DTR                                                ;
436                 DELR= DELD*DTR                                                ;
437                 ALFR= ALFD*DTR                                                ;
438                 PP  = 1.0 + SIN(PSIR)/COS(PSIR)                               ;
439                 PM  = 1.0 - SIN(PSIR)/COS(PSIR)                               ;
440                 NN = 0                                                        ;
441                 CN = -2.0 ; GR(1) = PSID + ALFD ; GR(2) = PSID + ALFD -2 ;
444               L5:
                    NN = NN + 1 ;
445                 IF NN > 15 THEN DO ;PUT DATA ( NN) ; BB1 = 100000 ; GO TO L2 ; END   ;
451                 N = 1                                                         ;
452                 CN = -1.0 ;
453                 SSSOH = 0.0       ;
454               L5:
455                    GMD = GR(N)    ;    GMR = GMD*DTR                         ;
456                 SSSO= (PP*COS(GMR-ALFR) - PM*SIN(GMR-ALFR))*COS(GMR-ALFR)     ;
```

```
PRG: PROCEDURE OPTIONS (MAIN)

457              IF SSSO > SSSOH THEN DO ; SSSOH = SSSO ; GMDH = GR(N) ; END ;
462                IF SSSO > SSSO THEN TS(N) = 2 ; ELSE TS(N) = 1                    ;
465              IF N = 1 THEN DO ; N = 2 ; GO TO L5 ; END                           ;
470              IF N>54 | (ABS(SSSO-SSSO) < 0.00001) THEN DO          ;
472                 GO TO L6                                                         ;
473              END /* IF N>49 | SSSO=SSSO+-0.0001 */                              ;
478              IK = 0 ;
475              IF TS(N) ¬= TS(N-1) THEN DO ; IK = 1 ; CN = -CN/4 ; END             ;
480                    GR(N+1) = GR(N) + CN                                         ;
481                    N = N + 1                                                    ;
482                    GO TO L5                                                     ;
483             L6:
484              IF N>54 & (ABS(SSSO-SSSO) > 0.00002) THEN DO          ;
485              SSSO = SSSOH ;
486                 GMD = GMDH ; GMR = GMD*DTR ; PUT DATA ( GMD , SSSO , SSSO ) ; END ;
490              CPPS= COS(PSIR) + SIN(PSIR)                                         ;
491              GMT = SIN(GMR)/COS(GMR)                                             ;
492              RC  = (SIN(GMR))/(PP*COS(GMR-ALFR)) - (TAN(PSIR))*(SIN(DELR))/
                                                     (PP*COS(ALFR+DELR))             ;
493              T2  = T1/RC                                                         ;
494              FIT = RC*COS(ALFR)/(1 - RC*SIN(ALFR))                               ;
495              PPIR=   ATAN(FIT)                                                   ;
496              E   = SIN(PPIR-ALFR)/COS(PPIR-ALFR) + COS(PPIR)/SIN(PPIR);
497              LT2R= COS(PSIR+ALFR+DELR)/(CPPS*COS(ALFR+DELR))                     ;
498              LT1R= LT2R/RC                                                       ;
499              LO  = LT1R*T1                                                       ;
500              LBP = T2/CPPS                                                       ;
501              LBP = LBP*SIN(PSIR)/COS(ALFR+DELR)                                  ;
502              ET1 = 0.1*E*VC*(1+RC)/(LBP*(PSIR+ALFR-GMR))                         ;
503              LAB = LBP*COS(PSIR)/COS(GMR-ALFR)                                   ;
504             L7:
                 SSSOH= SSSO                                                         ;
505              FC  = SO*W*(LBP*(SIN(PSIR+ALFR) + COS(PSIR+ALFR)) +
                        SSSO*LBP*(COS(DELR) - NOSO*SIN(DELR)))                       ;
506              FT  = SO*W*(LBP*(COS(PSIR+ALFR) - SIN(PSIR+ALFR)) +
                        SSSO*LBP*(SIN(DELR) + NOSO*COS(DELR)))                       ;
507              QP  = VC*RC*(FC*SIN(ALFR) + FT*COS(ALFR))/1000                      ;
508              THP = QP/(12*P*CP*VC*T1*W)                                          ;
509              QS  = FC*VC/1000 - QP                                               ;
510              R   = 720*P*CP*VC*T1/K                                              ;
511              THNB= R*FIT                                                         ;
512              B   = SQRT(ABS(R/LT2R))                                             ;
513              THNB = ABS(THNB)                                                    ;
514              IF THNB > 12.0  THEN BETA = 0.10;ELSE BETA = 0.475 - 0.1038*LOG(THNB);
517              THS = QS*(1-BETA)/(12*P*CP*VC*T1*W)                                 ;
518              TTHS= THS/(1-BETA)                                                  ;
519              THMX= 0.72*THP*B*(0.856**(B*LT2R*(PP-1)/2.5))                       ;
520              THMA= THMX + THS                                                    ;
521              THTR=   ATAN((RC*COS(PPIR)-SIN(ALFR-PPIR))/COS(ALFR-PPIR));
522              THTR= ABS(THTR)                                                     ;
523              THTD= THTR*RTD                                                      ;
524              TTHT=       ((RC*COS(PPIR) - SIN(ALFR-PPIR))/(COS(ALFR-PPIR)))      ;
525              TTHT = ABS(TTHT)                                                    ;
```

```
PR4: PROCEDURE OPTIONS (MAIN)                                                    ;

526              PPID = PPIR*RTD  ; BRD = ALPD + ATAND(PT/PC)                    ;
528              WKP = 1400*QP                                                   ;
529              WTL = PC*VC                                                     ;
530              WPD = WTL - WKP                                                 ;
531              WS=  (COS(PSIR+ALPR-GMR)-SIN(PSIR+ALPR-GMR))*SO*LBE/LAB         ;
532                N = 1 ; CH(1) = 0.0  ; CN = 2.0                               ;
535             L8:
536              CHID = CH(N)  ; CHIR = CHID*DTR                                 ;
537              AA = 1.0 + (2*COS(CHIR))*(SIN(GMR) - SIN(CHIR))                 ;
538              DD = SS*COS(GMR-CHIR) + WS*SIN(GMR-CHIR)                        ;
539              SI = DD/AA                                                      ;
540                  IF SI > SII THEN TS(N) = 1 ; ELSE TS(N) = 2                 ;
543                  IF N = 1 THEN DO ; N = 2 ; CH(N) = 2.0  ;GO TO L8 ; END     ;
549                  IF N > 35 THEN DO ; PUT DATA ( N,CHID,SI) ; GO TO L9 ; END  ;
554                  IF ABS(SII-SI) > 1.0 THEN DO                                ;
556                     IF TS(N) = TS(N-1) THEN DO                               ;
558                        CH(N+1) = CH(N) + CN                                  ;
559                        N = N + 1                                             ;
560                        GO TO L8                                              ;
561                     END  /* TS(I) = TS(N-1)  ?    */                       ;
562                     ELSE DO                                                  ;
563                        CN = -CN/4                                            ;
564                        CH(N+1) = CH(N) + CN                                  ;
565                        N = N + 1                                             ;
566                        GO TO L8                                              ;
567                     END     /* ELSE DO     */                               ;
568               END   /* ABS(SI-SII) > 1.0     */                            ;
569             L9:
                 H = LAB*(SIN(GMR) - SIN(CHIR))                                  ;
570              D = LAB*(COS(CHIR) - COS(GMR))                                  ;
571              APDZ = (LAB**2)*(PSIR+ALPR-CHIR)/2 + H*(H+D)/2                  ;
572              TRQ = LAB*(PSIR+ALPR-CHIR)/(VC*(1+RC))                          ;
573              WPT =  SO*W*((1-RC**2)/(2*RC) + TTRT)*APDZ/TRQ                  ;
574              SPSO = (PM/(TAN(PSIR)) + SSSO*((TAN(ALPR+DELR)) + WOSO))/
                        ((1/(TAN(PSIR))) - TAN(ALPR+DELR))                     ;
575              SPT1= SPSO*SO                                                   ;
576                 IF ABS(LO) < 0.0001 THEN LO = 0.01                           ;
578                 IF ABS(PP-1) < 0.0001 THEN PP = 1.01                         ;
580              ET2 = 0.4*VC*RC/(LO*(PP-1))                                     ;
581              IF E > 5.3 THEN E = 5.3 ; IF E < 1.8 THEN E = 1.8 ;
585              IF ETI > 45000 THEN ET2 = 45000 ; IF ET2 < 300 THEN ET2 = 300 ;
589              IF THMA > 270 THEN THMA = 270 ; IF THMA < 150 THEN THMA = 150 ;
593              SPO = EXP(14.1042) ;
594              T = THMA/1000 ;
595              GK = EXP(-13.2560 ) ;
596              AA = -1.84670 ;
597              BB = 15.7909 ;
598              CC = -0.246249 ;
599              DD = 1.19791 - 1.36858*(LOG(E)) ;
600              SPE1 = SPO*(GK**T)*(E**(AA+BB*T))*(ET2**(CC+DD*T))    ;
601              SPT2 = SPE1 ;
602              RE1 = SPT1 - SPE1                                               ;
603              RE2 = WPT - WPD                                                 ;
```

```
PR4: PROCEDURE OPTIONS (MAIN)

604              IF TST = 3 THEN DO ;
606              PUT EDIT ( '....VC.....ALFD.....W.....T1.....T2.....FC.....',
                            'FT.....FFID.....BED.....WTL.....WFD.....THS.....THMA')
                          ( SKIP(2) , A(55) , A(58) , A(6)  )                    ;
607              PUT EDIT   (VC,ALFD,W,T1,T2,FC,FT,FFID,BED,WTL,WFD,THS,THMA,'...')
                            ( R(FMT01))                                          ;
608              PUT EDIT ('      LO        LBE       LBF       LAB       ET1       FT2'
                          ,'       R         WSD       NOSO      FPT       WKF      SFT2 '
                          ) ( A(60) , A(60)                                      );
609              PUT EDIT   (LO,LBE,LBF,LAB,ET1,FT2,F,WSD,NOSO,FPT,WKF,SFT2) (R(FMT03));
610              PUT EDIT ('     PSID      GMD       DELD        RC       LT1R      LT2R',
                          '    SFT1       CHID      SO         SS         NS         SSSO')
                          ( A(59) , X(1) , A(60)                                 );
611              PUT EDIT (PSID,GMD,DELD,RC,LT1R,LT2R,SFT1,CHID,SO,SS,NS,SSSO) (R(FMT02))
                                                                                 ;
612               PUT EDIT ('ITERATIONS ON TEST NUMBER ', I ,' ARE COMPLETE WHERE ' ,
                            'THE CUTTING SPEED = ',VC , ' THE RAKE ANGLE = ',ALFD ,
                            ' THE UNDEFORMED CHIP THICKNESS = ', T1 ) (A(26),F(5),A(20) ,
                            A(20),F(5,1),A(18), F(5,2), A(33), F(7,5)              );
613               PUT DATA ( SOP , SSSOP ,     T2 , RC )                         ;
614               KLL = KIL + 1                                                  ;
615               END ;
616               G(1) = RR1 ;   G(2) = RF2*PO/VC  ;
618               ET = 8 ; ET1T = ET1 ; TTHST = TTHS ; SOT = SO ; SST = SS ;
623              L2:
                     RETURN                                                      ;
624              END FNCTN                                                       ;
625              END /* PR4 */                                                  ;
```

```
....VC......ALFD......W......T1.......T2......FC.......FT......FFID......BED.....WTL.......WPD......THS......THMA
    490.0      45.0    0.279    0.0201    0.0459     336.6      79.8     24.27     58.34    161615     99460         74        266...
      LO         LBE       LBF       LAB       ET1       ET2         E          WSD       NOSO       WPT       WKF      SFT2
   0.0321     0.0436    0.0117    0.0440     15472     48956      1.83         0.00          1     99617     62154     32837
     PSID       GMD       DELD        RC      LT1R      LT2R      SFT1         CHID        SO         SS        NS      SSSO
     3.07      37.29      33.48     0.439     1.590     0.699   32747.1         14.5   18355.1   21299.5   14489.7    1.1604
ITERATIONS ON TEST NUMBER 43489 ARE COMPLETE WHERE THE CUTTING SPEED = 490.0 THE RAKE ANGLE = 45.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOF= 1.84730E+00        SSSOF= 1.15999E+00      T2= 4.59489E-02         RC= 4.39618E-01;

....VC......ALFD......W......T1.......T2......FC.......FT......FFID......BED.....WTL.......WPD......THS......THMA
    490.0      40.0    0.279    0.0201    0.0499     366.2      91.0     22.72     53.96    175793    116532         86        269...
      LO         LBE       LBF       LAB       ET1       ET2         E          WSD       NOSO       WPT       WKF      SFT2
   0.0339     0.0451    0.0120    0.0451     14566     29399      2.07         0.00          1    116574     59260     32132
     PSID       GMD       DELD        RC      LT1R      LT2R      SFT1         CHID        SO         SS        NS      SSSO
     6.40      34.21      25.33     0.404     1.678     0.679   32140.8         10.2   18500.0   22500.0   14192.8    1.1899
ITERATIONS ON TEST NUMBER 43488 ARE COMPLETE WHERE THE CUTTING SPEED = 490.0 THE RAKE ANGLE = 40.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOF= 1.82964E+00        SSSOF= 1.18999E+00      T2= 4.99293E-02         RC= 4.04571E-01;

....VC......ALFD......W......T1.......T2......FC.......FT......FFID......BED.....WTL.......WPD......THS......THMA
    490.0      35.0    0.279    0.0201    0.0550     372.1      109.9     20.85     51.46    178621    125140         91        260...
      LO         LBE       LBF       LAB       ET1       FT2         E          WSD       NOSO       WPT       WKF      SFT2
   0.0351     0.0477    0.0143    0.0471     15718     11935      2.37         0.01          1    125365     53480     30796
     PSID       GMD       DELD        RC      LT1R      LT2R      SFT1         CHID        SO         SS        NS      SSSO
     9.52      32.64      21.47     0.367     1.741     0.639   30807.8          9.7   17200.0   22500.0   13464.9    1.1999
ITERATIONS ON TEST NUMBER 43487 ARE COMPLETE WHERE THE CUTTING SPEED = 490.0 THE RAKE ANGLE = 35.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOF= 1.72557E+00        SSSOF= 1.19999E+00      T2= 5.50298E-02         RC= 3.67073E-01;

....VC......ALFD......W......T1.......T2......FC.......FT......FFID......BED.....WTL.......WPD......THS......THMA
    490.0      30.0    0.279    0.0201    0.0644     427.7      147.0     17.83     48.96    205330    154026        108        268...
      LO         LBE       LBF       LAB       ET1       ET2         E          WSD       NOSO       WPT       WKF      SFT2
   0.0423     0.0553    0.0157    0.0544     15303      7699      2.89         0.03          1    154025     51304     28794
     PSID       GMD       DELD        RC      LT1R      LT2R      SFT1         CHID        SO         SS        NS      SSSO
    10.45      28.12      20.34     0.313     2.094     0.656   28799.4          9.9   17111.6   20705.0   13274.6    1.2099
ITERATIONS ON TEST NUMBER 43486 ARE COMPLETE WHERE THE CUTTING SPEED = 490.0 THE RAKE ANGLE = 30.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOF= 1.71493E+00        SSSOF= 1.20999E+00      T2= 6.44866E-02         RC= 3.13243E-01;

....VC......ALFD......W......T1.......T2......FC.......FT......FFID......BED.....WTL.......WPD......THS......THMA
    490.0      25.0    0.279    0.0201    0.0824     523.6      212.4     13.90     47.98    251355    202715        135        270...
      LO         LBE       LBF       LAB       ET1       FT2         E          WSD       NOSO       WPT       WKF      SFT2
   0.0471     0.0666    0.0250    0.0640     12799      3960      3.84         0.00          1    202850     48639     31374
     PSID       GMD       DELD        RC      LT1R      LT2R      SFT1         CHID        SO         SS        NS      SSSO
    16.08      25.65      17.49     0.240     2.332     0.571   31366.3          8.6   16268.0   20823.1   11815.9    1.2799
ITERATIONS ON TEST NUMBER 43485 ARE COMPLETE WHERE THE CUTTING SPEED = 490.0 THE RAKE ANGLE = 25.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOF= 1.62090E+00        SSSOF= 1.27999E+00      T2= 8.24977E-02         RC= 2.44854E-01;

....VC......ALFD......W......T1.......T2......FC.......FT......FFID......BED.....WTL.......WPD......THS......THMA
    490.0      20.0    0.279    0.0201    0.0768     515.1      219.1     15.19     43.04    287250    199322        135        270...
      LO         LBE       LBF       LAB       ET1       FT2         E          WSD       NOSO       WPT       WKF      SFT2
   0.0405     0.0593    0.0261    0.0558     16489      3195      3.59         0.00          1    199039     48227     33673
     PSID       GMD       DELD        RC      LT1R      LT2R      SFT1         CHID        SO         SS        NS      SSSO
    21.30      28.52      14.38     0.262     2.005     0.527   33679.9          7.8   17097.5   21713.8   13684.9    1.2699
ITERATIONS ON TEST NUMBER 43484 ARE COMPLETE WHERE THE CUTTING SPEED = 490.0 THE RAKE ANGLE = 20.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOF= 1.69374E+00        SSSOF= 1.26999E+00      T2= 7.69128E-02         RC= 2.62976E-01;
```

```
....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    320.0      45.0     0.279   0.0201   0.0453    340.3     84.8    24.69    59.00   108927    66067       69      240...
      LO       LBE       LBF      LAB       RT1       RT2       E         WSD      NOSO      WPT       WKF      SFT2
  0.0280    0.0415    0.0138   0.0415     11126     21087      1.80      0.00         1    65791     42870     38177
    PSID      GMD       DELD       RC      LT1R      LT2R      SFT1      CHID      SO        SS        NS        SSSO
    5.49     40.15     29.29    0.445     1.390     0.619   38232.6      15.2   18688.6   21762.8   15044.8    1.1644
ITERATIONS ON TEST NUMBER 43329 ARE COMPLETE WHERE THE CUTTING SPEED = 320.0 THE RAKE ANGLE = 45.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.86704E+04        SSSOP= 1.16425E+00      T2= 4.53431E-02         RC= 4.05492E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    320.0      40.0     0.279   0.0201   0.0506    371.8     99.1    22.31    54.93   118980    78809       80      237...
      LO       LBE       LBF      LAB       RT1       RT2       E         WSD      NOSO      WPT       WKF      SFT2
  0.0327    0.0454    0.0135   0.0452     10007     12556      2.11      0.00         1    78818     40171     34326
    PSID      GMD       DELD       RC      LT1R      LT2R      SFT1      CHID      SO        SS        NS        SSSO
    7.06     35.12     25.58    0.398     1.622     0.646   34314.9      10.8   18500.0   22500.0   14329.3    1.1899
ITERATIONS ON TEST NUMBER 43328 ARE COMPLETE WHERE THE CUTTING SPEED = 320.0 THE RAKE ANGLE = 40.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.83069E+04        SSSOP= 1.18999E+00      T2= 5.05802E-02         RC= 3.98577E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    320.0      35.0     0.279   0.0201   0.0557    376.5     118.3    20.55    52.45   120508    84198       84      230...
      LO       LBE       LBF      LAB       RT1       RT2       E         WSD      NOSO      WPT       WKF      SFT2
  0.0333    0.0477    0.0161   0.0469     10925      7443      2.40      0.00         1    84379     36309     33476
    PSID      GMD       DELD       RC      LT1R      LT2R      SFT1      CHID      SO        SS        NS        SSSO
   10.57     34.04     22.13    0.362     1.652     0.599   33488.9      10.6   17200.0   22500.0   13643.1    1.1999
ITERATIONS ON TEST NUMBER 43327 ARE COMPLETE WHERE THE CUTTING SPEED = 320.0 THE RAKE ANGLE = 35.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.72610E+04        SSSOP= 1.19999E+00      T2= 5.57173E-02         RC= 3.62544E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    320.0      30.0     0.279   0.0201   0.0762    491.1     185.4    14.80    50.68   157181   122754      114      252...
      LO       LBE       LBF      LAB       RT1       RT2       E         WSD      NOSO      WPT       WKF      SFT2
  0.0454    0.0640    0.0219   0.0627      8176      3420      3.51      0.00         1   122747     34426     31919
    PSID      GMD       DELD       RC      LT1R      LT2R      SFT1      CHID      SO        SS        NS        SSSO
   12.29     26.76     21.50    0.264     2.250     0.595   31918.5       9.6   16533.8   20803.5   11751.8    1.2582
ITERATIONS ON TEST NUMBER 43326 ARE COMPLETE WHERE THE CUTTING SPEED = 320.0 THE RAKE ANGLE = 30.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.65054E+04        SSSOP= 1.25887E+00      T2= 7.62756E-02         RC= 2.64828E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    320.0      25.0     0.279   0.0201   0.0828    522.1     230.1    13.83    48.79   167084   133598      122      267...
      LO       LBE       LBF      LAB       RT1       RT2       E         WSD      NOSO      WPT       WKF      SFT2
  0.0412    0.0654    0.0294   0.0622      9353      2259      3.86      0.00         1   133668     33485     37157
    PSID      GMD       DELD       RC      LT1R      LT2R      SFT1      CHID      SO        SS        NS        SSSO
   18.89     29.10     20.06    0.243     2.043     0.498   37137.3      11.3   16213.7   20753.5   12282.5    1.2799
ITERATIONS ON TEST NUMBER 43325 ARE COMPLETE WHERE THE CUTTING SPEED = 320.0 THE RAKE ANGLE = 25.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.60780E+04        SSSOP= 1.27999E+00      T2= 8.28694E-02         RC= 2.43756E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    320.0      20.0     0.279   0.0201   0.0805    513.4     239.9    14.45    45.04   164312   132118      122      267...
      LO       LBE       LBF      LAB       RT1       RT2       E         WSD      NOSO      WPT       WKF      SFT2
  0.0363    0.0610    0.0314   0.0570     11797      1997      3.78      0.00         1   132146     32193     39427
    PSID      GMD       DELD       RC      LT1R      LT2R      SFT1      CHID      SO        SS        NS        SSSO
   23.86     31.81     18.29    0.250     1.798     0.451   39421.5      12.4   16414.9   20846.9   13516.9    1.2699
ITERATIONS ON TEST NUMBER 43324 ARE COMPLETE WHERE THE CUTTING SPEED = 320.0 THE RAKE ANGLE = 20.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.62629E+04        SSSOP= 1.26999E+00      T2= 8.05258E-02         RC= 2.50850E-01;
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....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    240.0      45.0    0.279   0.0201   0.0454     343.8     87.2     24.65     59.24     82532     49980        65       219...
      LO        LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0267    0.0410    0.0147    0.0408      8343     18030      1.80      0.00         1     49980     32552     40701
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
     6.48     40.98     26.66     0.444     1.326     0.590   40639.2      14.2   18800.0   22500.0   15121.9    1.1699
ITERATIONS ON TEST NUMBER 43249 ARE COMPLETE WHERE THE CUTTING SPEED = 240.0 THE RAKE ANGLE = 45.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.87163E+04        SSSOP= 1.16980E+00      T2= 4.54063E-02         RC= 4.44872E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    240.0      40.0    0.279   0.0201   0.0512     376.1     105.3     22.01     55.65     90278     59777        76       216...
      LO        LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0319    0.0456    0.0146    0.0453      7677      8913      2.10      0.00         1     59769     30500     36113
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
     7.57     35.82     25.71     0.394     1.579     0.622   36102.0      11.2   18500.0   22500.0   14430.5    1.1899
ITERATIONS ON TEST NUMBER 43248 ARE COMPLETE WHERE THE CUTTING SPEED = 240.0 THE RAKE ANGLE = 40.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.83147E+04        SSSOP= 1.18999E+00      T2= 5.12635E-02         RC= 3.94042E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    240.0      35.0    0.279   0.0201   0.0559     378.0     123.2     20.46     53.05     90734     63179        79       211...
      LO        LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0317    0.0474    0.0174    0.0464      8491      5363      2.41      0.00         1     63191     27554     35744
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
    11.50     35.25     22.24     0.361     1.572     0.567   35783.4      11.4   17200.0   22500.0   13790.7    1.1999
ITERATIONS ON TEST NUMBER 43247 ARE COMPLETE WHERE THE CUTTING SPEED = 240.0 THE RAKE ANGLE = 35.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.72723E+04        SSSOP= 1.19999E+00      T2= 5.59160E-02         RC= 3.61255E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    240.0      30.0    0.279   0.0201   0.0786     500.5     196.9     14.31     51.47    120140     94237       109       233...
      LO        LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0434    0.0649    0.0250    0.0631      5994      2292      3.63      0.00         1     94206     25933     34605
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
    13.90     27.75     21.49     0.256     2.150     0.552   34605.4      10.9   16269.4   20745.2   11429.0    1.2751
ITERATIONS ON TEST NUMBER 43246 ARE COMPLETE WHERE THE CUTTING SPEED = 240.0 THE RAKE ANGLE = 30.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.62219E+04        SSSOP= 1.27599E+00      T2= 7.86705E-02         RC= 2.56766E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    240.0      25.0    0.279   0.0201   0.0919     552.0     262.6     12.37     50.43    132502    107651       120       252...
      LO        LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0404    0.0714    0.0364    0.0671      6512      1388      4.33      0.00         1    107650     24851     31588
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
    20.57     29.95     21.42     0.219     2.003     0.440   31592.3      13.8   15406.0   20204.3   11372.9    1.3114
ITERATIONS ON TEST NUMBER 43245 ARE COMPLETE WHERE THE CUTTING SPEED = 240.0 THE RAKE ANGLE = 25.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.55485E+04        SSSOP= 1.31202E+00      T2= 9.19494E-02         RC= 2.19685E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
    240.0      20.0    0.279   0.0201   0.0884     539.0     268.8     13.10     46.50    129379    105423       119       250...
      LO        LBE       LBF       LAB       ET1       ET2        E       WSD      NOSO       WPT       WKF      SFT2
   0.0360    0.0663    0.0372    0.0613      8205      1281      4.17      0.00         1    105425     23955     43361
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
    25.41     32.46     20.05     0.228     1.782     0.407   43353.0      14.5   15700.3   20343.7   12738.7    1.2957
ITERATIONS ON TEST NUMBER 43244 ARE COMPLETE WHERE THE CUTTING SPEED = 240.0 THE RAKE ANGLE = 20.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.55845E+04        SSSOP= 1.29514E+00      T2= 9.84367E-02         RC= 2.28411E-01;
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....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THNA
    160.0      45.0    0.279   0.0201   0.0514     370.5      94.9     21.03     59.37     59290     38604        67       180...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0342     0.0482    0.0142    0.0489      3929     10608      2.15      0.00         1     38613     20685     38365
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
    3.96      34.43      31.51     0.392     1.693     0.665   34366.0      13.5   17960.2   21572.0   12691.5    1.2010
ITERATIONS ON TEST NUMBER 43169 ARE COMPLETE WHERE THE CUTTING SPEED = 160.0 THE RAKE ANGLE = 45.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.78834E+04        SSSOP= 1.19979E+00      T2= 5.14347E-02         RC= 3.92730E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THNA
    160.0      40.0    0.279   0.0201   0.0593     410.0     120.2     18.44     56.34     65502     46247        77       185...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0382     0.0535    0.0162    0.0538      3809      4903      2.60      0.00         1     46267     19355     33265
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
    6.63      30.95      27.57     0.340     1.891     0.643   33239.1      11.8   17405.6   21337.3   11984.4    1.2258
ITERATIONS ON TEST NUMBER 43168 ARE COMPLETE WHERE THE CUTTING SPEED = 160.0 THE RAKE ANGLE = 40.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.73282E+04        SSSOP= 1.22647E+00      T2= 5.93859E-02         RC= 3.40147E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THNA
    160.0      35.0    0.279   0.0201   0.0704     459.8     158.6     15.71     54.32     73580     55507        89       193...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0411     0.0602    0.0212    0.0595      3686      2361      3.20      0.00         1     55514     18073     34201
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
   10.71      28.68      23.24     0.286     2.035     0.583   34199.0      11.5   16539.7   20895.6   11100.4    1.2633
ITERATIONS ON TEST NUMBER 43167 ARE COMPLETE WHERE THE CUTTING SPEED = 160.0 THE RAKE ANGLE = 35.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.65288E+04        SSSOP= 1.26336E+00      T2= 7.04065E-02         RC= 2.86904E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THNA
    160.0      30.0    0.279   0.0201   0.0831     520.3     213.6     13.46     52.32     83260     65959       101       209...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0413     0.0671    0.0296    0.0644      3730      1292      3.88      0.00         1     65960     17300     38412
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
   16.19      28.54      20.91     0.242     2.049     0.497   38412.2      12.0   15843.5   20718.8   10713.8    1.3077
ITERATIONS ON TEST NUMBER 43166 ARE COMPLETE WHERE THE CUTTING SPEED = 160.0 THE RAKE ANGLE = 30.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.58091E+04        SSSOP= 1.30775E+00      T2= 8.31716E-02         RC= 2.42871E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THNA
    160.0      25.0    0.279   0.0201   0.0977     576.8     282.7     11.59     51.11     92296     75761       111       225...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0387     0.0746    0.0416    0.0690      3972       809      4.63      0.00         1     75761     16535     46026
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
   22.84      30.54      20.97     0.206     1.920     0.396   46028.7      14.8   14944.1   20208.5   10612.0    1.3522
ITERATIONS ON TEST NUMBER 43165 ARE COMPLETE WHERE THE CUTTING SPEED = 160.0 THE RAKE ANGLE = 25.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.50798E+04        SSSOP= 1.35280E+00      T2= 9.77389E-02         RC= 2.06672E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THNA
    160.0      20.0    0.279   0.0201   0.0981     605.1     317.0     11.75     47.65     96831     80201       118       240...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0342     0.0723    0.0453    0.0652      4633       703      4.66      0.00         1     80207     16630     52618
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
   28.64      33.26      20.09     0.205     1.696     0.349   52611.0      13.8   15564.9   21221.7   12066.9    1.3634
ITERATIONS ON TEST NUMBER 43164 ARE COMPLETE WHERE THE CUTTING SPEED = 160.0 THE RAKE ANGLE = 20.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.54435E+04        SSSOP= 1.36228E+00      T2= 9.81341E-02         RC= 2.05840E-01;
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....VC......ALPD......W.......T1.......T2.......FC.......FT.......PFID.....BED.....WTL.......WPD.....THS.....THMA
    120.0      45.0     0.279    0.0201    0.0521     372.4     102.8     20.68     60.44     44689     29056        62       165...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0322     0.0480    0.0161    0.0485      3024      6545      2.19      0.00         1     29024     15633     37265
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
    5.03      35.62      29.89     0.387     1.596     0.618   37218.2      14.7   17751.7   21435.1   12653.8    1.2058
ITERATIONS ON TEST NUMBER 43129 ARE COMPLETE WHERE THE CUTTING SPEED = 120.0 THE RAKE ANGLE = 45.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.76550E+00       SSSOP= 1.20613E+00      T2= 5.21115E-02         RC= 3.87629E-01;

....VC......ALPD......W.......T1.......T2.......FC.......FT.......PFID.....BED.....WTL.......WPD.....THS.....THMA
    120.0      40.0     0.279    0.0201    0.0607     415.4     128.2     17.94     57.15     49858     35282        72       169...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0366     0.0539    0.0183    0.0539      2827      3177      2.68      0.00         1     35302     14576     35665
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
    7.80      31.69      26.44     0.332     1.812     0.602   35631.9      12.7   17178.6   21245.6   11720.9    1.2367
ITERATIONS ON TEST NUMBER 43128 ARE COMPLETE WHERE THE CUTTING SPEED = 120.0 THE RAKE ANGLE = 40.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.70842E+00       SSSOP= 1.23757E+00      T2= 6.07558E-02         RC= 3.32478E-01;

....VC......ALPD......W.......T1.......T2.......FC.......FT.......PFID.....BED.....WTL.......WPD.....THS.....THMA
    120.0      35.0     0.279    0.0201    0.0727     470.6     167.6     15.13     54.60     56482     42917        84       177...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0398     0.0613    0.0238    0.0602      2658      1563      3.33      0.00         1     42919     13565     36474
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
   12.06      29.08      22.46     0.277     1.974     0.548   36471.4      12.1   16288.5   20872.5   10648.0    1.2814
ITERATIONS ON TEST NUMBER 43127 ARE COMPLETE WHERE THE CUTTING SPEED = 120.0 THE RAKE ANGLE = 35.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.62765E+00       SSSOP= 1.28148E+00      T2= 7.27741E-02         RC= 2.77571E-01;

....VC......ALPD......W.......T1.......T2.......FC.......FT.......PFID.....BED.....WTL.......WPD.....THS.....THMA
    120.0      30.0     0.279    0.0201    0.0865     542.8     226.2     12.88     52.62     65143     52053        97       194...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0403     0.0687    0.0328    0.0654      2615       863      4.06      0.00         1     52054     13090     41392
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
   17.83      28.69      20.04     0.233     1.996     0.465   41391.3      11.8   15720.3   21011.9   10181.3    1.3366
ITERATIONS ON TEST NUMBER 43126 ARE COMPLETE WHERE THE CUTTING SPEED = 120.0 THE RAKE ANGLE = 30.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.56962E+04       SSSOP= 1.33747E+00      T2= 8.65525E-02         RC= 2.33384E-01;

....VC......ALPD......W.......T1.......T2.......FC.......FT.......PFID.....BED.....WTL.......WPD.....THS.....THMA
    120.0      25.0     0.279    0.0201    0.1031     610.0     303.5     10.94     51.45     73201     60684       107       212...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0377     0.0777    0.0462    0.0708      2710       537      4.92      0.00         1     60682     12516     50388
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
   24.82      30.62      20.12     0.195     1.869     0.365   50392.2      14.5   18723.0   20555.2    9937.5    1.3961
ITERATIONS ON TEST NUMBER 43125 ARE COMPLETE WHERE THE CUTTING SPEED = 120.0 THE RAKE ANGLE = 25.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.46302E+00       SSSOP= 1.39656E+00      T2= 1.03197E-01         RC= 1.95741E-01;

....VC......ALPD......W.......T1.......T2.......FC.......FT.......PFID.....BED.....WTL.......WPD.....THS.....THMA
    120.0      20.0     0.279    0.0201    0.1122     698.8     390.5     10.21     49.19     83960     70771       122       246...
      LO        LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
  0.0314     0.0812    0.0573    0.0705      2920       426      5.29      0.00         1     70769     13088     68742
    PSID       GMD       DELD        RC      LT1R      LT2R      SFT1      CHID        SO        SS        NS      SSSO
   32.74      34.34      19.97     0.179     1.558     0.289   68742.0      13.3   15243.3   22200.0   11120.5    1.4563
ITERATIONS ON TEST NUMBER 43124 ARE COMPLETE WHERE THE CUTTING SPEED = 120.0 THE RAKE ANGLE = 20.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019     SOP= 1.52352E+04       SSSOP= 1.45714E+00      T2= 1.12228E-01         RC= 1.79989E-01;
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....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
     80.0      45.0    0.279   0.0201   0.0534     378.5     112.3     20.04     61.53     30281     19785        56       150...
       LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
   0.0302    0.0483    0.0185    0.0485      2001      3534      2.27      0.00         1     19784     10496     41019
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1       CHID        SO        SS        NS      SSSO
     6.46     36.59     28.00     0.377     1.496     0.565   41020.1      15.8   17499.3   21308.1   12370.2    1.2176
ITERATIONS ON TEST NUMBER 43089 ARE COMPLETE WHERE THE CUTTING SPEED =  80.0 THE RAKE ANGLE = 45.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOP= 1.73766E+04        SSSOP= 1.21827E+00      T2= 5.30416E-02        RC= 3.77982E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
     80.0      40.0    0.279   0.0201   0.0635     424.7     139.0     17.02     58.13     33977     24321        65       150...
       LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
   0.0350    0.0552    0.0214    0.0549      1798      1745      2.84      0.00         1     24323      9655     38692
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1       CHID        SO        SS        NS      SSSO
     9.44     32.15     24.99     0.317     1.734     0.551   38690.1      14.1   16689.3   20985.1   11019.8    1.2573
ITERATIONS ON TEST NUMBER 43088 ARE COMPLETE WHERE THE CUTTING SPEED =  80.0 THE RAKE ANGLE = 40.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOP= 1.66230E+04        SSSOP= 1.25707E+00      T2= 6.35240E-02        RC= 3.17989E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
     90.0      35.0    0.279   0.0201   0.0769     495.6     180.2     14.21     54.98     39649     30574        78       158...
       LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
   0.0388    0.0633    0.0274    0.0618      1617       863      3.56      0.00         1     30573      9075     39732
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1       CHID        SO        SS        NS      SSSO
    14.07     28.93     20.77     0.262     1.922     0.508   39730.6      12.1   16040.8   21101.3    9778.4    1.3154
ITERATIONS ON TEST NUMBER 43087 ARE COMPLETE WHERE THE CUTTING SPEED =  80.0 THE RAKE ANGLE = 35.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOP= 1.60369E+04        SSSOP= 1.31646E+00      T2= 7.69056E-02        RC= 2.62659E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
     80.0      30.0    0.279   0.0201   0.0898     574.8     241.0     12.36     52.74     45986     37067        90       174...
       LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
   0.0393    0.0703    0.0358    0.0663      1617       514      4.24      0.00         1     37074      8918     45070
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1       CHID        SO        SS        NS      SSSO
    19.56     28.63     18.87     0.224     1.946     0.437   45061.6      10.8   15815.9   21667.8    9679.0    1.3699
ITERATIONS ON TEST NUMBER 43086 ARE COMPLETE WHERE THE CUTTING SPEED =  80.0 THE RAKE ANGLE = 30.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOP= 1.59060E+04        SSSOP= 1.36999E+00      T2= 8.98951E-02        RC= 2.24706E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
     90.0      25.0    0.279   0.0201   0.1099     688.8     343.4     10.23     51.51     55072     46224       104       200...
       LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
   0.0362    0.0813    0.0521    0.0723      1567       307      5.27      0.00         1     46222      8848     59328
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1       CHID        SO        SS        NS      SSSO
    27.80     30.36     18.27     0.183     1.794     0.329   59335.8      11.5   15102.0   22200.0    9223.0    1.4699
ITERATIONS ON TEST NUMBER 43085 ARE COMPLETE WHERE THE CUTTING SPEED =  80.0 THE RAKE ANGLE = 25.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOP= 1.51020E+04        SSSOP= 1.46999E+00      T2= 1.09968E-01        RC= 1.83688E-01;

....VC.....ALFD.....W.....T1.....T2.....FC.....FT.....PFID.....BED.....WTL.....WPD.....THS.....THMA
     80.0      20.0    0.279   0.0201   0.1206     742.1     407.4      9.47     48.76     59374     50844       112       208...
       LO       LBE       LBF       LAB       ET1       ET2         E       WSD      NOSO       WPT       WKF      SFT2
   0.0358    0.0873    0.0603    0.0751      1704       300      5.29      0.00         1     50853      8530     63420
     PSID       GMD      DELD        RC      LT1R      LT2R      SFT1       CHID        SO        SS        NS      SSSD
    32.60     31.74     18.69     0.167     1.775     0.297   63416.9      12.1   14800.0   22200.0    9947.6    1.5000
ITERATIONS ON TEST NUMBER 43084 ARE COMPLETE WHERE THE CUTTING SPEED =  80.0 THE RAKE ANGLE = 20.00 THE UNDEFORMED CHIP
THICKNESS = 0.02019      SOP= 1.48000E+04        SSSOP= 1.50000E+00      T2= 1.20627E-01        RC= 1.67457E-01;
```

PR2: PROCEDURE OPTIONS (MAIN)

```
1               PR2: PROCEDURE OPTIONS (MAIN)                                   ;
2               DCL E(99) , ET(99) , T(99) , S(99) ,          SO(99) , A(99) , B(7) ,
                      R(10,99) , NT(99) FIXED BINARY (31,0) ,  SO(99) , SS(99) ,
                  (LE(99) , LT(99) , LSO(99) , LSS(99) , LSP(99) , LS(99) ) DECIMAL  ;
3                    NTROL = 1  ;
4               STT:
5               LE(*) = 0 ; LT(*) = 0 ; T(*) = 0 ;
7               LS(*) = 10**37 ;
8               S(*) = 10**37 ;
9               NTS = 29 ;
10              DO M = 1 TO NTS                                                 ;
11                IF NTROL = 1 THEN DO ;
13                 GET EDIT ( NT(M) , E(M) , ET(M) , T(M) , SO(M) , SS(M) , CM)
                                ( 6 F(12,3) , F(8,3))                           ;
14              END ;
15                IF NTROL = 2 THEN DO ;
17              GET EDIT ( NT(M) , E(M) , ET(M) , T(M) , SO(M) )
                   ( F(12,1) ,  3 F(15,3) ,  F(23,9)  )                         ;
18              END ;
19              S(M) = SO(M) ;
20                 T(M) = T(M)/1000                                             ;
21                 LE(M) = LOG( P(M))                                           ;
22                 LT(M) = LOG(ET(M))                                           ;
23                 LS(M) = LOG(SO(M))                                           ;
24              END /* DO M = 1 TO NTS */                                       ;
25               DO Q = -1 , 0 , 1 ;   IF Q = 1 THEN P = 0 ; ELSE P = 1 ;
29              DO M = 1 TO NTS ;
30              LS(M) = P*LOG(SS(M)) + Q*LOG(SO(M)) ;
31              S(M) = ((SS(M))**P)*((SO(M))**Q)     ;
32              END ;
33                 R(*,*) = 0.0 ;
34                 R(1,*) = 1/LS(*) ;
35                 R(2,*) = T(*)/LS(*) ;
36                 R(3,*) = LE(*)/LS(*) ;
37                 R(4,*) = LE(*)*T(*)/LS(*) ;
38                 R(5,*) = LT(*)*T(*)/LS(*) ;
39                 R(6,*) = LT(*)*LE(*)*T(*)/LS(*) ;
40                 R(7,*) = LT(*)/LS(*) ;
41              DO M = 2 TO 7 ;
42              B(*) = 0.0 ;
43              M = 0 ;
44                 DO I = 1 TO N ;
45                 DO J = 1 TO N ;
46                   M = M + 1 ; A(M) = SUM(R(I,*)*R(J,*)) ; END ; B(I) = SUM(R(I,*));
50                 END   /* DO I = 1 TO N  */  ;
51              PUT EDIT (':') ( PAGE , K(119) , A(1)) ;
52                  CALL PR5 ( A , B , N ) ;
53              PUT DATA (B)                                                    ;
54                SPO = EXP(B(1)) ;  GK = EXP(B(2)) ; PUT DATA ( SPO , GK ) ;
57              LSP(*) = B(1) + T(*)*B(2) + LE(*)*B(3) + LE(*)*T(*)*B(4) +
                         LT(*)*T(*)*B(5) + LT(*)*LE(*)*T(*)*B(6) + LT(*)*B(7)   ;
59              SPSO = 0.0 ;
59              NPT = 29 ;
```

```
PR2: PROCEDURE OPTIONS (MAIN)                                          ;

60              DO M = 1 TO NPT ;
61              PSP = EXP(LSP(M))                                                ;
62              EPSP = 100*(PSP-S(M))/S(M)                                       ;
63              PUT EDIT (  NT(M) , S(M) , PSP , EPSP ) ( SKIP , F(5) , 3 F(12,3))  ;
64              SPSQ = SPSQ + ( S(M) - PSP)**2  ;
65             END ;
66             LST:
                RMSQ =   100*(SQRT(SPSQ/30)) ;
67              PUT DATA ( RMSQ ) ;
68              END ; END ;
70                IF NTROL = 1 THEN DO ;   NTROL = 2 ; GO TO STT ; END ;
75             PR5: PROCEDURE      (AH , BH , MM  )                             ;
76              ON ZERODIVIDE GO TO LL4 ;    ON UNDERFLOW GO TO LL4             ;
80              ON OVERFLOW GO TO LL4       ;  ON FIXEDOVERFLOW GO TO LL4       ;
84              DECLARE   A(49) , B(7) , AH(60) , BH(10)                         ;
85              DO KKK = 1 TO (MM*MM) ; A(KKK) = AH(KKK) ;  END ; N = MM         ;
89              DO KKK = 1 TO N ; B(KKK) = BH(KKK)  ;  END                       ;
92              DO M = 1 TO N                                                    ;
93              PUT EDIT ((A(N*L+M) DO L = 0 TO (N-1)), B(M)) (SKIP ,(N+1) F(12,6))  ;
94              END                                                              ;
95              TOL =.0.0001                                                     ;
96              KS = 0                                                           ;
97              JJ = -N                                                          ;
98              DO J = 1 TO N                                                    ;
99                JY = J+1                                                       ;
100               JJ = JJ+N+1                                                    ;
101               BIGA = 0.0                                                     ;
102               IT = JJ-J                                                      ;
                  /* SEARCH FOR MAX COEFFICIENT IN COLUMN          */
103               DO I = J TO N                                                  ;
104                 IJ = IT+I                                                    ;
105                 IF ( ABS(BIGA) - ABS(A(IJ))) < 0.0 THEN DO                   ;
107                   BIGA = A(IJ)                                               ;
108                   IMAX = I                                                   ;
109                 END  /* (ABS(BIGA) - ABS(A(IJ))) < 0.0                  */ ;
110               END  /* I = J TO N */                                          ;
                  /* TEST FOR PIVOT LESS THAN TO L              */
                  /* INTERCHANGE ROWS IF NECESSARY  */
111               I1 = J+N*(J-2)                                                 ;
112               IT = IMAX-J                                                    ;
113               DO K = J TO N                                                  ;
114                 I1 = I1+N                                                    ;
115                 I2 = I1 + IT                                                 ;
116                 SAVE = A(I1)                                                 ;
117                 A(I1) = A(I2)                                                ;
118                 A(I2) = SAVE                                                 ;
                    /*  DIVIDE EQUATION BY LEADING COEFFICIENT  */
119                 A(I1) = A(I1)/BIGA                                           ;
120               END  /* IF ( ABS(DO K = J TO N          */                    ;
121               SAVE = B(IMAX)                                                 ;
122               B(IMAX) = B(J)                                                 ;
123               B(J) = SAVE/BIGA                                               ;
124               IF J = N THEN GO TO BKSOL                                      ;
```

```
PR2: PROCEDURE OPTIONS (MAIN)

                  /* ELIMINATE NEXT VARIABLE                    */
126               IQS = N*(J-1)                                              ;
127               DO IX = JY TO N                                            ;
128                 IXJ = IQS + IX                                           ;
129                 IT = J - IX                                              ;
130                 DO JX = JY TO N                                          ;
131                   IXJX = N*(JX-1) + IX                                   ;
132                   JJX = IXJX + IT                                        ;
133                   A(IXJX) = A(IXJX) - (A(IXJ))*A(JJX)                    ;
134                 END   /* DO JX = JY TO N       */                       ;
135                 B(IX) = B(IX) - (B(J))*(A(IXJ))                          ;
136               END   /* DO IX = JY TO N                    */            ;
137               END   /* J = 1 TO N              */                       ;
138             BKSOL:      /* BACK SOLUTION         */
                  NY = N-1                                                   ;
139               IT = N*N                                                   ;
140               DO J = 1 TO NY                                             ;
141                 IA = IT - J                                              ;
142                 IB = N - J                                               ;
143                 IC = N                                                   ;
144                 DO K = 1 TO J                                            ;
145                   B(IB) = B(IB) - (A(IA))*(B(IC))                        ;
146                   IA = IA - N                                            ;
147                   IC = IC - 1                                            ;
148                 END  /* DO K = 1 TO J         */                       ;
149               END   /* DO J = 1 TO NY      */                           ;
150               DO KKK = 1 TO N ; BN(KKK) = B(KKK) ; END                   ;
153               DO M = 1 TO N                                              ;
154               PUT EDIT ((A(N*L+M) DO L = 0 TO (N-1)), B(M)) (SKIP ,(N+1) F(12,6))  ;
155               END                                                        ;
156             LL4:
                  RETURN                                                   ;
157               END PR5                                                    ;
158             END /*PR2*/                                                  ;
```

```
  624.126953    86.132904   130.810592
   86.132904    12.746530    19.155075
    1.000000     0.138005     0.032609
   86.132904     1.000000     1.282411          B(1)= 3.26099E-02    B(2)= 1.28241E+00    B(3)= 0.00000E+00
B(4)= 0.00000E+00        B(5)= 0.00010E+00      B(6)= 0.00000E+00    B(7)= 0.00000E+00;   SPO= 1.03310E+00
GK= 3.60532E+00;
43089        1.229        1.196       -2.671
43129        1.209        1.188       -1.733
43169        1.196        1.184       -1.046
43249        1.183        1.180       -0.325
43329        1.167        1.172        0.443
43489        1.171        1.166       -0.365
43088        1.283        1.240       -3.341
43128        1.250        1.228       -2.075
43168        1.224        1.216       -0.723
43248        1.202        1.209        0.553
43328        1.190        1.202        0.998
43488        1.190        1.196        0.497
43087        1.360        1.314       -3.380
43127        1.310        1.288       -1.988
43167        1.262        1.260       -0.165
43247        1.228        1.247        1.600
43327        1.211        1.236        2.046
43487        1.201        1.226        2.036
43086        1.421        1.383       -2.715
43126        1.369        1.346       -1.669
43166        1.322        1.320       -0.188
43246        1.285        1.301        1.292
43326        1.249        1.277        2.222
43486        1.216        1.250        2.807
43085        1.462        1.424       -2.558
43125        1.411        1.391       -1.375
43165        1.362        1.359       -0.224
43245        1.322        1.343        1.538
43325        1.295        1.324        2.242          RMSD= 2.18457E+00;
```

```
  624.126953   86.132904  619.010498  130.810592
   86.132904   12.746530   91.648910   19.155075
  619.010498   91.648910  660.296386  137.670013
    1.000000    0.138005    0.991802    0.032360
   86.132904    1.000000    7.450911    1.541179
  619.010498    0.859726    1.000000   -0.035754B(1)= 3.23601E-02      B(2)= 1.54117E+00      B(3)=-3.57547E-02
B(4)= 0.00000E+00      B(5)= 0.00000E+00      B(6)= 0.00000E+00      B(7)= 0.00000E+00;     SFO= 1.03288E+00
GK= 8.67009E+00;
43089       1.229       1.197      -2.619
43129       1.209       1.188      -1.723
43169       1.196       1.184      -1.022
43249       1.183       1.180      -0.269
43329       1.167       1.174       0.586
43489       1.171       1.169      -0.115
43088       1.283       1.238      -3.565
43128       1.250       1.221      -2.358
43168       1.224       1.213      -0.914
43248       1.202       1.208       0.483
43328       1.190       1.202       1.066
43488       1.190       1.198       0.647
43087       1.360       1.313      -3.501
43127       1.310       1.281      -2.218
43167       1.262       1.257      -0.435
43247       1.228       1.245       1.443
43327       1.211       1.235       1.977
43487       1.201       1.225       1.929
43086       1.421       1.388      -2.377
43126       1.369       1.347      -1.565
43166       1.322       1.320      -0.148
43246       1.285       1.302       1.303
43326       1.249       1.276       2.177
43486       1.216       1.247       2.562
43085       1.462       1.432      -2.057
43125       1.411       1.396      -1.038
43165       1.362       1.361      -0.117
43245       1.322       1.344       1.612
43325       1.295       1.325       2.308      RMSQ= 2.14674E+00;
```

```
  624.126953   86.132904  619.010498   91.648895  130.810592
   86.132904   12.746530   91.648910   14.556415   19.155075
  619.010498   91.648910  660.296386  104.636795  137.670013
   91.648895   14.556415  104.636795   17.711868   21.684661
    1.000000    0.138005    0.991802    0.146843    0.334815
   86.132904    1.000000    7.450911    2.208122   -3.403320
  619.010498    0.859726    1.000000   -0.083171    0.067197
   91.648895    1.908375   -0.183641    1.000000    1.891843
B(3)= 6.719708E-02      B(4)= 1.89184E+00       B(5)= 0.00000E+00       B(6)= 0.00000E+00       B(7)= 0.00000E+00;
SFO= 1.39768E+00        GK= 3.32626E-02;
43089       1.229       1.190      -3.188
43129       1.209       1.193      -1.307
43169       1.196       1.192      -0.370
43249       1.183       1.189       0.471
43329       1.167       1.183       1.359
43489       1.171       1.176       0.428
43088       1.283       1.242      -3.222
43128       1.250       1.236      -1.134
43168       1.224       1.221      -0.320
43248       1.202       1.205       0.239
43328       1.190       1.189      -0.032
43488       1.190       1.181      -0.784
43087       1.360       1.326      -2.545
43127       1.310       1.292      -1.340
43167       1.262       1.266       0.334
43247       1.228       1.239       0.916
43327       1.211       1.219       0.677
43487       1.201       1.217       1.292
43086       1.421       1.388      -2.332
43126       1.369       1.349      -1.438
43166       1.322       1.309      -0.972
43246       1.285       1.283      -0.110
43326       1.249       1.257       0.626
43486       1.216       1.252       2.905
43085       1.462       1.466       0.253
43125       1.411       1.410      -0.013
43165       1.362       1.377       1.116
43245       1.322       1.348       1.931
43325       1.295       1.314       1.414       RMSQ= 1.74347E+00;
```

```
  624.126953   86.132904  619.010498   91.648895  736.513183  130.810592
   86.132904   12.746530   91.648910   14.556415  107.961090   19.155075
  619.010498   91.648910  660.296386  104.636795  776.242675  137.670013
   91.648895   14.556415  104.636795   17.711868  122.042526   21.684661
  736.513183  107.961090  776.242675  122.042526  920.776855  161.579864
    1.000000    0.146584    1.053941    0.165703    1.250183    0.113628
   86.132904    1.000000    7.243497    2.198455    8.173068    1.805624
  619.010498    0.911865    1.000000    0.046628   -3.941774   -0.012397
   91.648895    1.122151   -0.084095    1.000000  -32.723373    0.340303
  624.126953    0.120822   -0.005322    0.018555    1.000000   -0.161770B(1)= 1.13628E-01      B(2)= 1.80562E+00
B(3)=-1.23976E-02      B(4)= 3.40303E-01      B(5)=-1.61770E-01      B(6)= 0.00000E+00      B(7)= 0.00000E+00;
SFO= 1.12033E+00      GK= 6.08377E+00;
43089       1.229       1.224      -0.408
43129       1.209       1.208      -0.080
43169       1.196       1.198       0.185
43249       1.183       1.187       0.291
43329       1.167       1.174       0.584
43489       1.171       1.162      -0.737
43088       1.283       1.272      -0.916
43128       1.250       1.242      -0.605
43168       1.224       1.227       0.227
43248       1.202       1.209       0.567
43328       1.190       1.195       0.421
43488       1.190       1.181      -0.764
43087       1.360       1.356      -0.385
43127       1.310       1.303      -0.545
43167       1.262       1.266       0.292
43247       1.228       1.238       0.854
43327       1.211       1.219       0.669
43487       1.201       1.200      -0.071
43086       1.421       1.430       0.618
43126       1.369       1.365      -0.264
43166       1.322       1.320      -0.166
43246       1.285       1.283      -0.133
43326       1.249       1.248      -0.076
43486       1.216       1.214      -0.187
43085       1.462       1.477       1.049
43125       1.411       1.410      -0.057
43165       1.362       1.357      -0.381
43245       1.322       1.321      -0.096
43325       1.295       1.290      -0.407      RMSQ= 5.89783E-01;
```

```
  624.126953   86.132904  619.010498   91.648895  736.513183  776.242675  130.810592
   86.132904   12.746530   91.648910   14.556415  107.961090  122.042556   19.155075
  619.010498   91.648910  660.296386  104.636795  776.242675  877.791015  137.670013
   91.648895   14.556415  104.636795   17.711868  122.042526  147.047607   21.684661
  736.513183  107.961090  776.242675  122.042526  920.776855 1030.567382  161.579864
  776.242675  122.042556  877.791015  147.047607 1030.567382 1229.704833  181.014465
    1.000000    0.157222    1.130820    0.189435    1.327634    1.584175    0.117229
   86.132904    1.000000    7.238224    2.216387    7.678998   17.716308    1.944751
  619.010498   -5.673248    1.000000   -0.038096   -1.492310   -1.721129   -0.017408
   91.648895    0.147179   -0.066362    1.000000   -28.913238  -24.428405    0.227688
  736.513183   -7.835083    0.059402    0.021621    1.000000    1.403723   -0.179894
  624.126953   -0.795469    0.002679    0.002996   -0.192892    1.000000    0.016155
B(2)= 1.94475E+00      B(3)=-1.74084E-02      B(4)= 2.27688E-01      B(5)=-1.79894E-01      B(6)= 1.61554E-02
B(7)= 0.00000E+00;     SF0= 1.12437E+00       GK= 6.99189E+00;
43089       1.229       1.225      -0.338
43129       1.209       1.208      -0.032
43169       1.196       1.199       0.220
43249       1.183       1.187       0.306
43329       1.167       1.174       0.581
43489       1.171       1.162      -0.763
43088       1.283       1.271      -0.923
43128       1.250       1.242      -0.610
43168       1.224       1.227       0.228
43248       1.202       1.209       0.560
43328       1.190       1.194       0.404
43488       1.190       1.180      -0.803
43087       1.360       1.355      -0.419
43127       1.310       1.302      -0.575
43167       1.262       1.266       0.274
43247       1.228       1.238       0.842
43327       1.211       1.219       0.650
43487       1.201       1.200      -0.107
43086       1.421       1.429       0.538
43126       1.369       1.365      -0.282
43166       1.322       1.320      -0.155
43246       1.285       1.283      -0.105
43326       1.249       1.248      -0.061
43486       1.216       1.214      -0.196
43085       1.462       1.476       0.973
43125       1.411       1.410      -0.042
43165       1.362       1.358      -0.331
43245       1.322       1.322      -0.014
43325       1.295       1.291      -0.325       RESQ= 5.76557E-01;
```

```
  624.126953   96.132904  619.010498   91.648895  736.513183  776.242675 5379.683593  130.810592
   86.132904   12.746530   91.648910   14.556415  107.961090  122.042556  736.513183   19.155075
  619.010498   91.648910  660.296386  104.636795  776.242675  877.791015 5289.812500  137.670013
   91.648895   14.556415  104.636795   17.711868  122.042526  147.047607  776.242675   21.684661
  736.513183  107.961090  776.242675  122.042526  920.776855 1030.567382 6339.351562  161.579864
  776.242675  122.042556  877.791015  147.047607 1030.567382 1229.704833 6620.015625  181.014465
 5379.683593  736.513183 5289.812500  776.242675 6339.351562 6620.015625 6658.593750 1114.195800
    1.000000    0.136906    0.983294    0.144291    1.178386    1.230558    8.673110   -0.004875
   86.132904    1.000000    7.261648    2.222094    7.346454   17.406021   -7.128889    3.592204
  619.010498    6.902435    1.000000   -0.012623   -2.592805   -2.713879  -19.766647   -0.016740
   91.648895    2.009097   -0.070388    1.000000  -43.174942  -38.944717 -303.502441   -0.494263
  736.513183    7.127746    0.274505   -0.065087    1.000000    1.017687    7.598006   -0.369175
  776.242675    0.954386    0.024505    0.007746   -0.153156    1.000000   -6.134042    0.098999
  624.126953    0.685943    0.328977    0.022424    0.070603   -0.040079    1.000000    0.013971B(1)=-4.87589E-03
B(2)= 3.59220E+00       B(3)=-1.67404E-02       B(4)=-4.94263E-01       B(5)=-3.69175E-01       B(6)= 0.89996E-02
B(7)= 1.39716E-02;      SRD= 9.95135E-01        GS= 3.63140E+01;
43089       1.229       1.225      -0.337
43129       1.209       1.208      -0.065
43169       1.196       1.198       0.192
43249       1.193       1.187       0.296
43329       1.167       1.174       0.599
43489       1.171       1.162      -0.711
43088       1.283       1.272      -0.894
43128       1.250       1.242      -0.622
43168       1.224       1.227       0.226
43248       1.202       1.209       0.560
43328       1.190       1.194       0.393
43488       1.190       1.180      -0.829
43087       1.360       1.355      -0.402
43127       1.310       1.303      -0.554
43167       1.262       1.266       0.292
43247       1.228       1.238       0.852
43327       1.211       1.219       0.636
43487       1.201       1.200      -0.131
43086       1.421       1.429       0.562
43126       1.369       1.365      -0.246
43166       1.322       1.321      -0.106
43246       1.285       1.284      -0.087
43326       1.249       1.248      -0.082
43496       1.216       1.213      -0.202
43085       1.462       1.474       0.848
43125       1.411       1.410      -0.053
43165       1.362       1.358      -0.322
43245       1.322       1.322       0.006
43325       1.295       1.291      -0.325       RMSQ= 5.59506E-01;
```

```
     0.292032     0.045670     2.910132
     0.045670     0.007701     0.455084
     1.000000     0.156390     9.973781
     0.045670     1.000000    -0.055555
B(4)= 0.00000E+00       B(5)= 0.00000E+00
GK= 9.45959E-01;
43089    22495.300    21320.437       -5.222
43129    21779.003    21326.843       -2.076
43169    21616.609    21330.058       -1.325
43249    21446.996    21333.230       -0.530
43329    21541.496    21339.050       -0.939
43489    21951.199    21343.629       -2.767
43088    21316.796    21286.812       -0.140
43128    20774.300    21299.015        2.525
43168    20727.597    21305.457        2.787
43248    21105.410    21310.761        0.972
43328    21616.691    21316.187       -1.390
43488    21923.500    21320.519       -2.750
43087    20934.898    21233.550        1.426
43127    20669.996    21255.167        2.831
43167    20459.695    21272.406        3.972
43247    20808.304    21281.656        2.274
43327    21055.695    21290.039        1.112
43487    20763.703    21297.738        2.571
43086    21937.703    21186.843       -3.422
43126    21397.496    21211.652       -0.868
43166    21461.402    21229.683       -1.079
43246    21416.605    21242.544       -0.812
43326    21294.507    21260.113       -0.161
43486    20253.003    21279.628        5.069
43085    21642.496    21159.664       -2.230
43125    21564.906    21181.328       -1.778
43165    21096.699    21202.691        0.502
43245    20937.593    21213.875        1.319
43325    21102.109    21226.464        0.589
```

B(1)= 9.97378E+00 B(2)=-5.55551E-02 B(3)= 0.00000E+00
B(6)= 0.00000E+00 B(7)= 0.00000E+00; SPO= 2.14564E+04

RMSQ= 4.56106E+04;

```
    0.292032    0.045670    0.327606    2.910132
    0.045670    0.007701    0.055009    0.455084
    0.327606    0.055009    0.393718    3.264145
    1.000000    0.167913    1.201803    9.999094
    0.045670    1.000000    6.941495    2.547584
    0.292032    0.000032    1.000000   -0.385461B(1) = 9.99909E+00      B(2) = 2.54758E+00      B(3) =-3.85461E-01
B(4) = 0.00000E+00      B(5) = 0.00000E+00      B(6) = 0.00000E+00      B(7) = 0.00000E+00;     SPO= 2.20065E+04
GK= 1.27762E+01;
43089    22495.300    21587.003      -4.037
43129    21779.003    21515.750      -1.208
43169    21616.609    21559.785      -0.262
43249    21446.996    21650.738       0.949
43329    21541.496    21878.992       1.566
43489    21951.199    22155.648       0.931
43088    21316.796    20789.441      -2.473
43128    20774.300    20714.218      -0.289
43168    20727.597    20957.292       1.108
43248    21105.410    21259.585       0.730
43328    21616.691    21600.925      -0.072
43488    21923.500    21810.910      -0.513
43087    20934.898    20799.039      -0.648
43127    20669.996    20649.050      -0.101
43167    20459.695    20642.257       0.892
43247    20808.304    20941.207       0.638
43327    21055.695    21176.179       0.572
43487    20763.703    21123.191       1.731
43086    21937.703    21678.605      -1.181
43126    21397.496    21227.902      -0.792
43166    21461.402    21157.789      -1.414
43246    21416.605    21148.056      -1.253
43326    21294.507    21098.449      -0.920
43486    20253.003    20743.277       2.420
43085    21642.496    21948.101       1.412
43125    21564.906    21639.750       0.347
43165    21096.699    21194.746       0.464
43245    20937.593    21163.863       1.080
43325    21102.109    21201.820       0.472      RMSQ= 2.65034E+04;
```

```
    0.292032    0.045670    0.327606    0.055009    2.910132
    0.045670    0.007701    0.055009    0.009873    0.455084
    0.327606    0.055009    0.393718    0.070246    3.264145
    0.055009    0.009873    0.070246    0.013257    0.548118
    1.000000    0.167913    1.201803    0.218424    9.855410
    0.045670    1.000000    6.981495    2.261244    4.903636
    0.292032    0.000032    1.000000   -0.084067   -0.437919
    0.055009    0.000636   -0.000105    1.000000   -0.880898
B(3)=-4.37919E-01      B(4)=-8.80894E-01      B(5)= 0.00000E+00      B(6)= 0.00000E+00      B(7)= 0.00000E+00;
SPO= 1.90612E+04       GK= 1.34779E+02;
43089   22495.300   21638.511      -3.808
43129   21779.003   21462.464      -1.453
43169   21616.609   21482.101      -0.622
43249   21446.996   21563.960       0.545
43329   21541.496   21788.976       1.148
43489   21951.199   22088.539       0.625
43088   21316.796   20752.855      -2.645
43128   20774.300   20586.308      -0.904
43168   20727.597   20891.000       0.788
43248   21105.410   21276.683       0.811
43328   21616.691   21705.765       0.412
43488   21923.500   21952.015       0.130
43087   20934.898   20723.960      -1.007
43127   20669.996   20572.589      -0.471
43167   20459.695   20570.468       0.541
43247   20808.304   20993.796       0.891
43327   21055.695   21303.996       1.179
43487   20763.703   21182.035       2.014
43086   21937.703   21726.207      -0.964
43126   21397.496   21250.383      -0.687
43166   21461.402   21266.218      -0.909
43246   21416.605   21308.015      -0.507
43326   21294.507   21262.101      -0.152
43486   20253.003   20707.503       2.244
43085   21642.896   21778.566       0.628
43125   21564.906   21589.968       0.116
43165   21096.699   21112.378       0.074
43245   20937.593   21166.324       1.092
43325   21102.109   21317.304       1.019       RMSQ= 2.51087E+04;
```

```
    0.292032    0.045670    0.327606    0.055009    0.379511    2.910132
    0.045670    0.007701    0.055009    0.009873    0.063261    0.455084
    0.327606    0.055009    0.393718    0.070246    0.452270    3.264145
    0.055009    0.009873    0.070246    0.013257    0.080291    0.548114
    0.379511    0.063261    0.452270    0.080291    0.523504    3.781414
    1.000000    0.166692    1.191716    0.211564    1.373414    9.669666
    0.045670    1.000000    6.784734    2.251497    7.751526    9.024670
    0.327606    0.000399    1.000000    0.062283   -4.618090   -0.492552
    0.055009    0.000703   -0.000081    1.000000  -34.566223   -2.162377
    0.292032    0.000088   -0.000017    0.000012    1.000000   -0.120091B(1)= 9.66966E+00      B(2)= 9.02467E+00
B(3)=-4.92552E-01      B(4)=-2.16237E+00      B(5)=-1.20091E-01      B(6)= 0.00000E+00      B(7)= 0.00000E+00;
SPO= 1.58300E+04      GR= 8.30547E+03;
43089   22495.300   22079.777      -1.847
43129   21779.003   21630.218      -0.683
43169   21616.609   21537.058      -0.369
43249   21486.996   21497.820       0.236
43329   21541.496   21621.371       0.370
43489   21951.199   21849.425      -0.463
43088   21316.796   21106.195      -0.987
43128   20774.300   20647.101      -0.612
43168   20727.597   20957.992       1.111
43248   21105.410   21313.769       0.987
43328   21616.691   21767.210       0.696
43488   21923.500   21942.933       0.088
43087   20934.898   21039.859       0.501
43127   20669.996   20674.765       0.023
43167   20459.695   20548.039       0.431
43247   20808.304   20978.906       0.819
43327   21055.695   21302.511       1.172
43487   20763.703   20963.167       0.960
43086   21937.703   22158.859       1.008
43126   21397.496   21403.148       0.026
43166   21461.402   21378.812      -0.384
43246   21416.605   21299.464      -0.546
43326   21294.507   21152.804      -0.665
43486   20253.003   20225.671      -0.134
43085   21642.496   21807.996       0.764
43125   21568.906   21517.308      -0.220
43165   21096.699   20829.667      -1.265
43245   20937.593   20818.585      -0.568
43325   21102.109   21015.932      -0.408      RMSQ= 1.09709E+04;
```

```
    0.292032    0.045670    0.327606    0.055009    0.379511    0.452270    2.910132
    0.045670    0.007701    0.055009    0.009873    0.063261    0.080291    0.455084
    0.327606    0.055009    0.393718    0.070246    0.452270    0.572010    3.264145
    0.055009    0.009873    0.070246    0.013257    0.080291    0.106872    0.548114
    0.379511    0.063261    0.452270    0.080291    0.523504    0.657674    3.781414
    0.452270    0.080291    0.572010    0.106872    0.657674    0.867514    4.506116
    1.000000    0.177529    1.264753    0.236302    1.454162    1.918133    9.718111
    0.045670    1.000000    5.761841    2.267619    7.313968   17.476501   11.524127
    0.327606   -0.003150    1.000000   -0.035426   -1.595391   -1.958060   -0.575324
    0.055009    0.000107   -0.000052    1.000000  -30.882980  -29.432968   -3.957736
    0.379511   -0.004112    0.000089    0.000013    1.000000    1.478090   -0.423331
    0.292032   -0.000406   -0.000004    0.000002   -0.000107    1.000000    0.249101
B(1)= 9.718111E+00
B(2)= 1.152418+01       B(3)=-5.753248-01       B(4)=-3.957738+00       B(5)=-4.233318-01       B(6)= 2.491018-01
B(7)= 0.000008+00;      SFO= 1.661598+04        GK= 1.011268+05;
43089   22495.300   22388.929      -0.472
43129   21779.003   21827.179       0.221
43169   21616.609   21672.238       0.257
43249   21446.996   21541.390       0.440
43329   21541.496   21589.597       0.223
43489   21951.199   21722.726      -1.040
43088   21316.796   21151.636      -0.774
43128   20774.300   20654.742      -0.575
43168   20727.597   20973.746       1.187
43248   21105.410   21282.570       0.839
43328   21616.691   21694.136       0.358
43488   21923.500   21775.246      -0.676
43087   20934.898   20887.656      -0.225
43127   20669.996   20610.488      -0.287
43167   20459.695   20497.464       0.184
43247   20808.304   20919.949       0.536
43327   21055.695   21207.058       0.718
43487   20763.703   20783.535       0.095
43086   21937.703   22001.519       0.290
43126   21397.496   21391.046      -0.030
43166   21461.402   21426.859      -0.160
43246   21416.605   21362.609      -0.252
43326   21294.507   21146.531      -0.694
43486   20253.003   20102.027      -0.745
43085   21642.496   21650.652       0.037
43125   21564.906   21600.578       0.165
43165   21096.699   20976.785      -0.568
43245   20937.593   21031.593       0.448
43325   21102.109   21211.468       0.518       PMSQ= 1.048918+04;
```

```
     0.292032     0.045670     0.327606     0.055009     0.379511     0.452270     2.453555     2.910132
     0.045670     0.007701     0.055009     0.009873     0.063261     0.080291     0.379511     0.455084
     0.327606     0.055009     0.393718     0.070246     0.452270     0.572010     2.723141     3.264145
     0.055009     0.009873     0.070246     0.013257     0.080291     0.106872     0.452270     0.548119
     0.379511     0.063261     0.452270     0.080291     0.523504     0.657674     3.176957     3.781414
     0.452270     0.080291     0.572010     0.106872     0.657674     0.867518     3.745814     4.506116
     2.453555     0.379511     2.723141     0.452270     3.176957     3.745814    20.762664    24.449050
     1.000000     0.154678     1.109875     0.184332     1.294837     1.526687     8.462277    13.028878
     0.045670     1.000000     6.777787     2.274337     6.972425    17.130538    -7.878376   -33.861724
     0.327606     0.004335     1.000000    -0.003884    -2.961212    -3.317168   -20.572586    -0.534207
     0.055009     0.001364    -0.000054     1.000000   -43.399826   -43.204467  -280.449462    15.834304
     0.379511     0.004559     0.000155    -0.000038     1.000000     1.100068     7.013899     4.769542
     0.452270     0.000637     0.000001     0.000005    -0.000075     1.000000    -5.931029    -2.034223
     0.292032     0.000499     0.000098     0.000014     0.000021    -0.000024     1.000000    -0.380808B(1)= 1.30288E+01
B(2)=-3.38617E+01       B(3)=-5.34207E-01       B(4)= 1.58383E+01       B(5)= 4.76954E+00       B(6)=-2.03422E+00
B(7)=-3.80808E-01;      SFO= 4.55375E+05        GK= 1.96806E-15;
43089    22495.300    22323.031       -0.765
43129    21779.003    21983.085        0.937
43169    21616.609    21804.234        0.867
43249    21446.996    21557.687        0.516
43329    21541.496    21425.449       -0.538
43489    21951.199    21332.679       -2.817
43088    21316.796    21047.281       -1.264
43128    20778.300    20796.003        0.104
43168    20727.597    21032.975        1.472
43248    21105.410    21303.261        0.937
43328    21616.691    21751.500        0.623
43488    21923.500    21915.515       -0.036
43087    20934.898    20842.085       -0.443
43127    20669.996    20564.078       -0.512
43167    20459.695    20489.589        0.146
43247    20808.304    20929.449        0.582
43327    21055.695    21334.003        1.321
43487    20763.703    20982.750        1.054
43086    21937.703    21773.855       -0.746
43126    21397.496    21160.593       -1.107
43166    21861.402    21145.058       -1.474
43246    21816.605    21278.109       -0.665
43326    21294.507    21305.640        0.052
43486    20253.003    20233.312       -0.097
43085    21642.496    22237.656        2.749
43125    21564.906    21557.011       -0.036
43165    21096.699    20883.671       -1.009
43245    20937.593    20889.924       -0.228
43325    21102.109    21200.367        0.465       RMSQ= 2.11079E+04;
```

```
     0.306418     0.048084     2.980889
     0.048084     0.008136     0.466946
     1.000000     0.156925     9.948768
     0.048084     1.000000    -1.405884
B(4)= 0.00000E+00        B(5)= 0.00000E+00
GK= 2.45150E-01;
43089    18298.511    17815.742       -2.638
43129    18011.007    17951.656       -0.329
43169    18064.402    18020.148       -0.244
43249    18115.105    18087.933       -0.149
43329    18451.300    18213.464       -1.288
43489    18743.207    18312.390       -2.298
43088    16604.292    17118.140        3.094
43128    16611.898    17368.058        4.551
43168    16921.097    17501.339        3.429
43248    17551.800    17612.132        0.343
43328    18163.003    17725.972       -2.406
43488    18415.507    17817.207       -3.248
43087    15384.398    16066.472        4.433
43127    15774.800    16485.703        4.506
43167    16205.199    16827.390        3.839
43247    16941.703    17013.265        0.422
43327    17376.011    17184.042       -1.104
43487    17277.000    17341.941        0.375
43086    15427.800    15195.671       -1.504
43126    15626.101    15652.324        0.167
43166    16224.003    15992.593       -1.426
43246    16663.304    16241.339       -2.532
43326    17040.804    16582.929       -2.686
43486    16649.199    16972.589        1.942
43085    14799.703    14710.085       -0.605
43125    15282.199    15095.734       -1.220
43165    15481.097    15485.878        0.030
43245    15827.406    15693.980       -0.843
43325    16283.605    15931.246       -2.163

B(1)= 9.94876E+00        B(2)=-1.40588E+00        B(3)= 0.00000E+00
B(6)= 0.00000E+00        B(7)= 0.00000E+00;       SFO= 2.09264E+04

RMSQ= 3.59560E+04;
```

```
    0.306419     0.048084     0.344847     2.980889
    0.048084     0.008136     0.058095     0.466946
    0.344847     0.058095     0.415674     3.348868
    1.000000     0.168467     1.205387     9.972346
    0.048084     1.000000     6.929051     0.946582
    0.306419     0.000035     1.000000    -0.348972B(1) = 9.97234E+00       B(2) = 9.46582E-01       B(3) =-3.48972E-01
B(4) = 0.00000E+00       B(5) = 0.00000E+00       B(6) = 0.00000E+00       B(7) = 0.00000E+00;      SPO= 2.14256E+04
GK= 2.57688E+00;
43089    18298.511    18020.421       -1.519
43129    18011.007    18099.132        0.489
43169    18064.402    18199.574        0.748
43249    18115.105    18335.527        1.216
43329    18451.300    18634.699        0.993
43489    18743.207    18946.917        1.086
43088    16604.292    16756.511        0.916
43128    16611.898    16937.437        1.959
43168    16921.097    17244.308        1.910
43248    17551.800    17576.308        0.139
43328    18163.003    17943.062       -1.210
43488    18415.507    18191.000       -1.219
43087    15384.398    15766.363        2.482
43127    15774.800    16058.554        1.799
43167    16205.199    16375.884        1.050
43247    16941.703    16767.273       -1.029
43327    17376.011    17101.921       -1.577
43487    17277.000    17214.812       -0.359
43086    15427.800    15509.898        0.532
43126    15626.101    15659.789        0.215
43166    16224.003    15941.140       -1.743
43246    16663.304    16178.179       -2.935
43326    17040.804    16468.039       -3.361
43486    16649.199    16585.285       -0.383
43085    14799.703    15199.296        2.700
43125    15292.199    15386.191        0.680
43165    15481.097    15476.769       -0.027
43245    15827.406    15657.214       -1.075
43325    16283.605    15911.917       -2.282       RMSQ= 2.37746E+04;
```

```
    0.306418    0.048084    0.344847    0.058095    2.980889
    0.048084    0.008136    0.058095    0.010459    0.466946
    0.344847    0.058095    0.415674    0.074387    3.348868
    0.058095    0.010459    0.074387    0.014076    0.563269
    1.000000    0.168467    1.205387    0.215710    9.503749
    0.048084    1.000000    6.929051    2.262593    8.624809
    0.306418    0.000035    1.000000   -0.084018   -0.519515
    0.058095    0.000671   -0.000110    1.000000   -2.871274
B(1)= 9.50374E+00       B(2)= 8.62480E+00       B(3)=-5.19515E-01       B(4)=-2.87127E+00
B(5)= 0.00000E+00       B(6)= 0.00000E+00       B(7)= 0.00000E+00;
SPO= 1.34099E+04        GK= 5.56810E+03;
43089    18298.511    18160.062       -0.756
43129    18011.007    17952.410       -0.325
43169    18064.402    17985.515       -0.436
43249    18115.105    18095.785       -0.106
43329    18451.300    18384.187       -0.363
43489    18743.207    18758.300        0.080
43088    16604.292    16661.175        0.342
43128    16611.898    16599.257       -0.076
43168    16921.097    17067.105        0.862
43248    17551.800    17621.941        0.399
43328    18163.003    18227.660        0.355
43488    18415.507    18576.199        0.872
43087    15384.398    15583.242        1.292
43127    15774.800    15866.851        0.583
43167    16205.199    16191.652       -0.083
43247    16981.703    16905.468       -0.213
43327    17376.011    17440.859        0.373
43487    17277.000    17371.605        0.547
43086    15427.800    15623.125        1.266
43126    15626.101    15715.578        0.572
43166    16224.003    16210.453       -0.083
43246    16663.304    16577.554       -0.514
43326    17040.804    16888.933       -0.891
43486    16649.199    16493.031       -0.937
43085    14799.703    14822.132        0.151
43125    15282.199    15273.210       -0.058
43165    15481.097    15283.527       -1.276
43245    15827.406    15664.925       -1.026
43325    16283.605    16197.691       -0.527       RMSQ= 9.86341E+03;
```

```
    0.306418    0.048084    0.344847    0.058095    0.399246    2.980889
    0.048084    0.008136    0.058095    0.010459    0.066775    0.466946
    0.344847    0.058095    0.415674    0.074387    0.477247    3.348868
    0.058095    0.010459    0.074387    0.014076    0.084985    0.563269
    0.399246    0.066775    0.477247    0.084985    0.552110    3.878406
    1.000000    0.167254    1.195370    0.212864    1.382882    9.572257
    0.048084    1.000000    6.773320    2.252860    7.739502    7.109135
    0.344847    0.000418    1.000000    0.062543   -4.636077   -0.498711
    0.058095    0.000742   -0.000086    1.000000  -34.649826   -2.399552
    0.306418    0.000093   -0.000018    0.000013    1.000000    0.043356
B(1)= 9.57225E+00       B(2)= 7.10913E+00
B(3)=-4.98711E-01       B(4)=-2.39955E+00       B(5)= 4.33566E-02       B(6)= 0.00000E+00       B(7)= 0.00000E+00;
SPO= 1.43607E+04        GK= 1.22308E+03;
43089   18298.511   18027.589      -1.480
43129   18011.007   17902.382      -0.603
43169   18064.402   17969.503      -0.525
43249   18115.105   18116.402       0.007
43329   18451.300   18435.804      -0.083
43489   18743.207   18831.914       0.473
43088   16604.292   16560.945      -0.261
43128   16611.898   16583.468      -0.171
43168   16921.097   17048.476       0.752
43248   17551.800   17610.957       0.337
43328   18163.003   18207.976       0.247
43488   18415.507   18577.332       0.878
43087   15384.398   15499.589       0.748
43127   15774.800   15839.910       0.412
43167   16205.199   16199.480      -0.035
43247   16941.703   16909.933      -0.187
43327   17376.011   17440.527       0.371
43487   17277.000   17436.734       0.924
43086   15427.800   15511.656       0.543
43126   15626.101   15675.015       0.313
43166   16224.003   16178.996      -0.277
43246   16663.304   16578.976      -0.506
43326   17040.804   16919.421      -0.712
43486   16649.199   16634.898      -0.085
43085   14799.703   14815.546       0.107
43125   15292.199   15291.910       0.063
43165   15481.097   15358.921      -0.789
43245   15827.406   15759.117      -0.431
43325   16283.605   16280.542      -0.018       RMSQ= 8.65358E+03;
```

```
     0.306418    0.048084    0.344847    0.058095    0.399246    0.477247    2.980889
     0.048084    0.008136    0.058095    0.010459    0.066775    0.084985    0.466946
     0.344847    0.058095    0.415674    0.074387    0.477247    0.605229    3.348868
     0.058095    0.010459    0.074387    0.014076    0.084985    0.113384    0.563269
     0.399246    0.066775    0.477247    0.084985    0.552110    0.695539    3.878406
     0.477247    0.084985    0.605229    0.113384    0.695539    0.919620    4.628789
     1.000000    0.178073    1.268166    0.237579    1.457396    1.926925    9.609584
     0.048084    1.000000    6.750127    2.268885    7.303263   17.468063    8.784224
     0.344847   -0.003312    1.000000   -0.035221   -1.597477   -1.962958   -0.554608
     0.058095    0.000113   -0.000055    1.000000  -31.042663  -29.684585   -3.629442
     0.399246   -0.004319    0.000095    0.000014    1.000000    1.489620   -0.167581
     0.306418   -0.000426   -0.000005    0.000002   -0.000113    1.000000    0.173826
B(2)= 8.784228+00      B(3)=-5.546088-01      B(4)=-3.629448+00      B(5)=-1.675818-01      B(6)= 1.738268-01
B(7)= 0.000008+00;     SFO= 1.490698+04       GK= 6.530408+03;
43089   18298.511   18199.921     -0.538
43129   18011.007   18015.457      0.024
43169   18064.402   18048.386     -0.088
43249   18115.105   18142.871      0.153
43329   18451.300   18417.914     -0.180
43489   18743.207   18756.261      0.069
43088   16604.292   16585.304     -0.114
43128   16611.898   16589.890     -0.132
43168   16921.097   17058.316      0.810
43248   17551.800   17592.339      0.230
43328   18163.003   18162.796     -0.001
43488   18015.507   18475.089      0.323
43087   15384.398   15421.550      0.241
43127   15778.800   15806.906      0.203
43167   16205.199   16173.472     -0.195
43247   16981.703   16876.394     -0.385
43327   17376.011   17384.097      0.046
43487   17277.000   17332.535      0.321
43086   15427.800   15432.128      0.028
43126   15626.101   15668.062      0.268
43166   16224.003   16202.632     -0.131
43246   16663.304   16611.183     -0.312
43326   17040.804   16914.257     -0.742
43486   16649.199   16567.171     -0.492
43085   14799.703   14742.343     -0.387
43125   15282.199   15333.867      0.338
43165   15481.097   15437.000     -0.284
43245   15827.406   15873.117      0.288
43325   16283.605   16385.968      0.628      RMSQ= 5.311448+03;
```

```
    0.263739     0.055824     2.765046
    0.055824     0.012175     0.584620
    1.000000     0.211666    10.865621
    0.055824     1.000000    -1.802980
B(4)= 0.00000E+00       B(5)= 0.00000E+00
GK= 1.64806E-01;
43089    42632.031    40004.156       -6.164
43129    37698.023    38836.640        3.020
43169    34059.011    37957.148       11.445
43249    30693.992    36430.277       18.688
43329    31731.992    34832.300        9.770
43489    32672.992    32328.394       -1.054
43088    41127.035    39818.640       -3.181
43128    37776.007    38533.675        2.005
43168    29895.000    38196.050       27.767
43248    27983.015    36467.472       30.320
43328    27377.992    35150.015       28.387
43488    27209.011    32961.550       21.142
43087    41359.015    39097.104       -5.468
43127    37492.007    37852.351        0.961
43167    33372.011    37193.289       11.450
43247    29662.015    35682.035       20.295
43327    27184.011    34773.386       27.918
43487    25951.015    32994.007       27.139
43086    48631.015    37734.496      -22.406
43126    43278.039    36499.101      -15.663
43246    36792.031    33915.261       -7.819
43166    40872.007    35499.496      -12.286
43326    34994.019    32986.648       -5.736
43486    31831.011    31743.738       -0.274
43085    56805.015    36974.660      -34.909
43125    52583.019    35313.511      -32.842
43165    51245.011    34236.332      -33.190
43245    39992.027    33200.558      -16.982
43325    35642.007    32378.839       -9.155
```

B(1)= 1.38656E+01 B(2)=-1.80298E+00 B(3)= 0.00000E+00
B(6)= 0.00000E+00 B(7)= 0.00000E+00; SPO= 5.23455E+04

RMSQ= 7.08201E+05;

```
     0.263739     0.055824     0.293575     2.765046
     0.055824     0.012175     0.062208     0.584620
     0.293575     0.062208     0.350118     3.089327
     1.000000     0.211898     1.192600    10.331525
     0.055824     1.000000   -12.615931    -1.897634
     0.263739    -0.000061     1.000000     0.497817B(1)= 1.03315E+01       B(2)=-1.89763E+00       B(3)= 4.97817E-01
B(4)= 0.00000E+00       B(5)= 0.00000E+00       B(6)= 0.00000E+00       B(7)= 0.00000E+00;      SPO= 3.06849E+04
GK= 1.49922E-01;
43089    42632.031    34544.558      -18.970
43129    37698.023    33034.746      -12.370
43169    34059.011    31877.460       -6.405
43249    30693.992    30098.078       -1.941
43329    31731.992    27869.242      -12.173
43489    32672.992    25030.667      -23.390
43088    41127.035    39624.914       -3.652
43128    37776.007    37177.046       -1.585
43168    29895.000    35640.171       19.217
43248    27983.015    32834.046       17.335
43328    27377.992    30480.613       11.332
43488    27209.011    27796.964        2.160
43087    41359.015    45060.187        8.948
43127    37492.007    41388.726       10.393
43167    33372.011    38742.496       16.092
43247    29662.015    35481.050       19.617
43327    27184.011    33250.339       22.315
43487    25951.015    30895.515       19.053
43086    48631.015    46879.359       -3.601
43126    43278.039    43396.820        0.274
43246    36792.031    37022.398        0.626
43166    40472.007    40249.570       -0.549
43326    34994.019    34350.832       -1.837
43486    31831.011    31937.316        0.333
43085    56805.015    48726.324      -14.221
43125    52583.019    44502.699      -15.366
43165    51245.011    41681.730      -18.661
43245    39992.027    39188.039       -2.010
43325    35642.007    36765.691        3.152       RMSQ= 4.25332E+05;
```

```
    0.263739    0.055824    0.293575    0.062208    2.765046
    0.055824    0.012175    0.062208    0.013563    0.584620
    0.293575    0.062208    0.350118    0.074297    3.089327
    0.062208    0.013563    0.074297    0.016198    0.653962
    1.000000    0.211898    1.192600    0.253077   10.426337
    0.055824    1.000000    0.282781    1.191730   -2.342193
    0.263739   -0.000061    1.000000    0.213231    0.408604
    0.062208    0.000346   -0.004466    1.000000    0.817998
B(3) = 4.08604E-01      B(4) = 4.17998E-01      B(5) = 0.00000E+00      B(6) = 0.00000E+00      B(7) = 0.00000E+00;
SFO= 3.37365E+04        GR= 9.61165E-02;
43089    42632.031    38781.546      -19.414
43129    37698.023    33220.765      -11.876
43169    34059.011    32019.503       -5.988
43249    30693.992    30148.378       -1.777
43329    31731.992    27809.769      -12.360
43489    32672.992    24774.464      -24.174
43088    41127.035    39593.109       -3.729
43128    37776.007    37194.921       -1.538
43168    29895.000    35693.238       19.395
43248    27993.015    32860.734       17.430
43328    27377.992    30456.117       11.243
43488    27209.011    27652.968        1.631
43087    41359.015    44742.113        8.179
43127    37492.007    41256.238       10.040
43167    33372.011    38690.468       15.936
43247    29662.015    35477.972       19.607
43327    27184.011    33240.953       22.284
43487    25951.015    30852.675       18.888
43086    48631.015    46577.042       -4.223
43126    43278.039    43297.480        0.044
43246    36792.031    37117.425        0.894
43166    40472.007    40256.671       -0.532
43326    34994.019    34433.914       -1.600
43486    31831.011    31998.562        0.526
43085    56805.015    48471.367      -14.670
43125    52583.019    44546.261      -15.283
43165    51245.011    41851.812      -18.329
43245    39992.027    39436.093       -1.390
43325    35642.007    37020.632        3.867      RMSQ= 4.24024E+05;
```

```
    0.263739    0.055824    0.293575    0.062208    0.463028    2.765046
    0.055824    0.012175    0.062208    0.013563    0.101920    0.584620
    0.293575    0.062208    0.350118    0.074297    0.493960    3.089327
    0.062208    0.013563    0.074297    0.016198    0.108670    0.653962
    0.463028    0.101920    0.493960    0.108670    0.877681    4.835453
    1.000000    0.220118    1.066804    0.234695    1.895525    9.184440
    0.055824    1.000000  -15.303975   -2.236349   25.907684   28.875244
    0.293575   -0.000112    1.000000    0.213524   -0.952242    0.604701
    0.062208   -0.000129    0.005956    1.000000   -5.952471   -9.024642
    0.263739   -0.002228    0.000930    0.000011    1.000000   -1.912057B(1) = 9.18444E+00       B(2) = 2.88752E+01
B(3) = 6.04701E-01       B(4) =-9.02464E+00       B(5) =-1.91205E+00       B(6) = 0.00000E+00       B(7) = 0.00000E+00;
SPO= 9.74432E+03       GR= 3.47023E+12;
43089   42632.031   39803.226      -6.635
43129   37698.023   36618.093      -2.864
43169   34059.011   32728.191      -3.907
43249   30693.992   25935.773     -15.502
43329   31731.992   25772.351     -18.781
43489   32672.992   30583.894      -6.393
43088   41127.035   40963.765      -0.396
43128   37776.007   38772.210       2.637
43168   29895.000   33746.781      12.884
43248   27983.015   29442.046       5.213
43328   27377.992   27521.265       0.523
43488   27209.011   27003.062      -0.756
43087   41359.015   43301.078       4.695
43127   37492.007   41077.566       9.563
43167   33372.011   38413.000      15.105
43247   29662.015   34809.953      17.355
43327   27184.011   32183.105      18.389
43487   25951.015   28132.859       8.407
43086   48631.015   46618.550      -4.138
43126   43278.039   43921.683       1.487
43246   36792.031   39271.394       6.738
43166   40472.007   42576.203       5.199
43326   34994.019   37683.390       7.685
43486   31831.011   32683.339       2.677
43095   56805.015   46982.390     -17.291
43125   52583.019   44967.718     -14.482
43165   51245.011   42597.605     -16.874
43245   39992.027   38472.210      -3.800
43325   35642.007   36475.472       2.338       RMSQ= 3.61799E+05;
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    0.263739    0.055824    0.293575    0.062208    0.463028    0.493960    2.765046
    0.055824    0.012175    0.062208    0.013563    0.101920    0.108670    0.584620
    0.293575    0.062208    0.350118    0.074297    0.493960    0.567074    3.089327
    0.062208    0.013563    0.074297    0.016198    0.108670    0.124767    0.653962
    0.463028    0.101920    0.493960    0.108670    0.877681    0.895849    4.835453
    0.493960    0.108670    0.567074    0.124767    0.895849    0.987362    5.176922
    1.000000    0.219998    1.148013    0.252586    1.813603    1.998867   10.722923
    0.055824    1.000000   -5.504475   -0.060656   16.176544    8.302606    8.994637
    0.293575   -0.000105    1.000000    0.222020   -0.993042    0.808153   -0.779686
    0.062208   -0.000121    0.002211    1.000000   -4.798798   12.016633    8.233016
    0.463028    0.000055   -0.002462    0.000003    1.000000    4.676522   -0.456341
    0.263739   -0.002197   -0.021297   -0.000012   -0.000038    1.000000   -1.286008
B(2)= 8.99463E+00      B(3)=-7.79686E-01      B(4)= 8.20301E+00      B(5)=-4.56341E-01      B(6)=-1.28600E+00
B(7)= 0.00000E+00;     SPO= 4.53843E+04       GK= 8.05974E+03;
43089    42632.031    41136.214       -3.508
43129    37698.023    38357.871        1.750
43169    34059.011    35200.769        3.352
43249    30693.992    29466.992       -3.997
43329    31731.992    30111.113       -5.108
43889    32672.992    34147.117        4.511
43088    41127.035    37868.382       -7.923
43128    37776.007    35970.230       -4.780
43168    29895.000    32245.871        7.863
43248    27983.015    28764.464        2.792
43328    27377.992    27740.292        1.323
43488    27209.011    27077.437       -0.483
43087    41359.015    40221.980       -2.749
43127    37492.007    37690.222        0.528
43167    33372.011    34755.882        4.146
43247    29662.015    31226.421        5.274
43327    27184.011    28948.875        6.492
43487    25951.015    25156.113       -3.063
43086    48631.015    48697.199        0.136
43126    43278.039    44603.820        3.063
43246    36792.031    37117.496        0.884
43166    40472.007    41533.839        2.623
43326    34994.019    34052.093       -2.691
43486    31831.011    28634.378      -10.042
43085    56805.015    55999.160       -1.418
43125    52583.019    52963.902        0.724
43165    51245.011    48282.257       -5.781
43245    39992.027    41513.089        3.803
43325    35642.007    37041.574        3.926      RMSQ= 1.41249E+05;
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```
    0.263739    0.055824    0.293575    0.062208    0.463028    0.493960    2.166766    2.765046
    0.055824    0.012175    0.062208    0.013563    0.101920    0.108670    0.463028    0.584620
    0.293575    0.062208    0.350118    0.074297    0.493960    0.567074    2.310463    3.089327
    0.062208    0.013563    0.074297    0.016198    0.108670    0.124767    0.493961    0.653962
    0.463028    0.101920    0.493960    0.108670    0.877681    0.895849    3.952233    4.835453
    0.493960    0.108670    0.567074    0.124767    0.895849    0.987362    4.037564    5.176922
    2.166766    0.463028    2.310463    0.493961    3.952233    4.037564   18.319320   22.652999
    1.000000    0.213695    1.066318    0.227971    1.824023    1.863405    8.454682   14.065599
    0.055824    1.000000   12.961079    3.905218   -1.652958   21.491287  -44.553787  -11.090393
    0.293575   -0.000527    1.000000    0.214773   -0.965562    0.714235   -4.443655   -1.813988
    0.062208    0.000270    0.004459    1.000000   -3.792126   12.962867    1.109244   14.867738
    0.463028    0.002973   -0.038318    0.000003    1.000000    0.934003    6.784339    1.081575
    0.493960    0.000245   -0.000506   -0.000014   -0.000041    1.000000   -0.504532   -1.347826
    0.263739   -0.000535    0.019280    0.000031   -0.000031   -0.000054    1.000000   -0.255159B(1)= 1.40655E+01
B(2)=-1.10903E+01      B(3)=-1.81398E+00      B(4)= 1.48677E+01      B(5)= 1.08157E+00      B(6)=-1.34782E+00
B(7)=-2.55159E-01;     SPO= 1.28413E+06       GK= 1.52582E-05;
43089   42632.031   43095.378       1.086
43129   37698.023   38239.128       1.435
43169   34059.011   34431.320       1.093
43249   30693.992   29140.832      -5.060
43329   31731.992   30170.816      -4.919
43489   32672.992   33847.503       3.598
43088   41127.035   39291.476      -4.463
43128   37776.007   35764.039      -5.326
43168   29895.000   31791.300       6.343
43248   27983.015   28254.582       0.970
43328   27377.992   27611.015       0.851
43488   27209.011   27777.937       2.090
43087   41359.015   41191.410      -0.405
43127   37492.007   37411.144      -0.215
43167   33372.011   34080.261       2.122
43247   29662.015   30490.613       2.793
43327   27184.011   28523.804       4.928
43487   25951.015   25969.929       0.053
43086   48631.015   49075.625       0.914
43126   43278.039   44062.398       1.812
43246   36792.031   36377.437      -1.126
43166   40472.007   40490.769       0.046
43326   34994.019   33472.000      -4.349
43486   31831.011   29415.246      -7.589
43085   56805.015   56575.460      -0.404
43125   52583.019   52645.839       0.119
43165   51245.011   47960.507      -6.409
43245   39992.027   41985.093       4.983
43325   35642.007   37832.214       6.145       RMSQ= 1.21400E+05;
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BIBLIOGRAPHY*

1. Ernst, H. and Merchant, M. E., "Chip Formation, Friction and High Quality Machined Surfaces," Surface Treatment of Metals (American Society Metals), 1941, p. 259.

2. Merchant, M. E., "Mechanics of the Metal Cutting Process," J. Appl. Phys., Vol. 16, 1945, No. 5, p. 267 and No. 6, p. 318.

3. Bridgeman Phys. Rev., 1935, Vol. 48, p. 825, Proc. Amer. Acad. 1937, Vol. 71, p. 386, J. Appl. Phys., Vol. 8, 1937, No. 5, p. 328; J. Appl. Phys., Vol. 14, 1943, p. 273, "The Physics of High Pressure," 1949 (Bell & Sons, Limited, London).

4. Crossland, B., "The Effect of Fluid Pressure on the Shear Properties of Metals," Proc. Inst. Mech. Eng. (1954), Vol. 168, p. 935.

5. Lee, E. H. and Shaffer, B. W., "The Theory of Plasticity Applied to a Problem of Machining," J. Appl. Mech., Trans. Amer. Soc. Mech. Engrs., Vol. 73, p. 405.

6. Sata, Toshio, "Recent Developments Concerning Cutting Mechanics," Proceedings of the International Research in Production Engineering Conference, 1963, pp. 18-25.

7. Stabler, G. V., "The Fundamental Geometry of Cutting Tools," Proc. Inst. Mech. Engrs., London, Vol. 165, 1951, p. 14.

8. Huchs, H., "Plastizitatmechanische Grundlagen und Kenngrossen der Serspannung," Dissertation, Tech. Hock. Aachen, 1951.

9. Shaw, M. C., Cook, N. H., and Finnie, I., "The Shear-Angle Relationship in Metal Cutting," Trans. ASME, 1953, pp. 273-288.

10. Weisz, M., "Étudé Metallographique de la Formation du Copeau d'Usinage, l'Institute de Récherches de la Siderurgie," Ser. A., No. 142, 1957.

11. Colding, B. N., "A Yield Criterion Applied to the Shear Angle Relationship," Les Annales du College International pour L'Etude' Scientifique des Technique de Production Mechanique, Vol. 7, 1958.

---

* Abbreviations used conform to the practice of the Transaction of the American Society of Mechanical Engineers.

12. Sata, T. and Mizuno, M., "Friction Process on Cutting Tool and Cutting Mechanism," J. Sci. Res. Inst., Tokyo, Vol. 49, 1955, pp. 163-174.

13. Oxley, P. L. B., "A Strain-Hardening Solution for the 'Shear Angle' on the Orthogonal Metal Cutting," International J. Mech. Sci. Vol. 3, 1961, pp. 68-79.

14. Zorev, N. N., "Problems of Metal Cutting Mechanics," Moscoe, 1956.

15. Boothroyd, G. and Bailey, J. A., "Effects of Strain Rate and Temperature in Orthogonal Metal Cutting," J. Mech. Engr. Sci., Vol. 8, No. 3, 1961, pp. 264-275.

16. Bailey, J. A. and Singer, A. R. E., "Effect of Strain Rate and Temperature on the Resistance to Deformation of Aluminum, Two Aluminum Alloys and Lead," J. Inst. Metals, Vol. 92, 1964, p. 404.

17. Pugh, H. L. D., "Mechanics of the Cutting Process," Proceedings of the Conference on Technology of Engineering Manufacture.

18. Palmer, W. B. and Oxley, P. L. B., "Mechanics of Orthogonal Machining," Proc. Inst. Mech. Engrs., Vol. 173, 1959, p. 623.

19. Nakayama, K., "Studies on the Mechanism of Metal Cutting, Bull. Fac. Engrg. Natl. Univ. Yokohoma, Vol. 7, 1958, p. 1.

20. Wallace, P. W. and Boothroyd, G., "Tool Forces and Tool Chip Friction in Orthogonal Machining," J. Mech. Eng. Sci., Vol. 6, 1964, No. 1, p. 74.

21. Lubahn, J. D., "Derivation of Stress, Strain, Temperature, Strain-Rate Relation for Plastic Deformation," J. Appl. Mech., Sept. 1947, pp. A-229, A-230.

22. Albrecht, P., "Mechanics of the Cutting Process," Proceedings of the International Production Engineering Research Conference, 1963, pp. 32-41.

23. Shaw, M. C., "Resume and Critique of Papers in Part One," Proceedings of the International Production Engineering Research Conference, 1963, pp. 3-17.

24. Boothroyd, G., "Mechanics of Unlubricated Metal Cutting," The Engineer, Nov. 26, 1965.

25. Cumming, J. D., Kobayashi, S., and Thomsen, E. G., "A New Analysis of the Forces in Orthogonal Metal Cutting," J. Engr. for Ind., Nov. 1965, pp. 480-486.

26. Enahoro, H. E., "Effects of Cold Working on Chip Formation in Metal Cutting," Annals of the C.I.R.P., Vol. XIII, pp. 251-261.

27. Kobayashi, S., Herzog, R. P., Eggleston, D. M., and Thomsen, E. G., "A Critical Comparison of Metal Cutting Theories with New Experimental Data," J. Engr. for Ind., Nov. 1960, pp. 333-347.

28. Kobayashi, S. and Thomsen, E. G., "Metal Cutting Analysis - I," J. Engr. for Ind., Feb. 1962, pp. 63-70.

29. Kobayashi, S. and Thomsen, E. G., "Metal Cutting Analysis - II," J. Engr. for Ind., Feb. 1962, pp. 71-80.

30. Kullberg, G., "Mechanics of Orthogonal Cutting," Annals of the C.I.R.P., Vol. XII, No. 2, pp. 106-115.

31. Nakayama, N., "Mechanical Properties of Chips Produced on Metal Cutting," Proceedings of the International Research on Production Engineering Conference, 1963, pp. 83-88.

32. Ostafiev, V. A. and Kobayashi, Shiro, "Stress, Strain, and Strain-Rate in Metal Cutting," Proceedings of the 7th International M.T.D.R. Conference, U. of Birmingham, Sept. 1966, Pergamon Press, Oxford and N.Y.C., 1957.

33. Oxley, P. L. B., "Flow Stress Characteristics and the Machining Process," The Engineer, Jan. 27, 1967, pp. 140-144.

34. Oxley, P. L. B., "Mechanics of Metal Cutting," Proceedings of the International Research in Production Engineering Conference, 1963, pp. 50-60.

35. Oxley, P. L. B., "Rate of Strain Effect in Metal Cutting," J. Engr. for Ind., Nov. 1963, p. 335.

36. Oxley, P. L. B., "Mechanics of Metal Cutting for a Material of Variable Flow Stress," J. Engr. for Ind., Nov. 1963, p. 339.

37. Oxley, P. L. B., "Introducing Strain Rate Dependent Work Material Properties into the Analysis of Orthogonal Cutting," Annals of the C.I.R.P., Vol. XIII, 1966, pp. 127-138.

38. Rowe, G. W. and Spick, P. T., "A New Approach to Determinations of the Shear Plane Angle in Machining," J. Engr. for Ind., Aug. 1967, pp. 530-537.

39. Russell, J. K. and Brown, R. H., "Deformation During Chip Formation," J. Engr. for Ind., Feb. 1965, pp. 53-56.

40. Sata, Toshio, "Flow Stress in Metal Cutting," Sci. Pap. IPCR, Vol. 53, Sept. 1959, (Tokyo, Japan), pp. 188-200.

41. Thomsen, E. G., "Application of the Mechanics of Plastic Deformation to Metal Cutting," Annals of the C.I.R.P., Vol. XII, pp. 113-123.

42. Trigger, K. J., "Temperatures in Machining and Their Importance," Proceedings of the International Research in Production Engineering Conference, 1963, pp. 95-101.

43. Trigger, K. J. and von Turkovich, B. F., "Chip Formation in High Speed Cutting of Copper and Aluminum," J. Engr. for Ind., Nov. 1963, pp. 365-373.

44. von Turkovich, B. F., "Mechanics of Cutting," Proceedings of the International Research in Production Engineering Conference, 1963, pp. 26-31.

45. Weiner, J. H., "Shear Plane Temperature Distribution in Orthogonal Cutting and Discussion," Trans. of the ASME, Nov. 1965, pp. 1331-1341.

46. Zorev, N. N., "Interrelationship Between Shear Processes Occurring Along Tool Face and on Shear Plane in Metal Cutting," Proceedings of International Production Engineering Research Conference, 1963, pp. 42-49.

47. Boothroyd, G., "A Metal Cutting Dynamometer," The Engineer, Feb. 23, 1962.

48. Boothroyd, G., "Temperatures in Orthogonal Metal Cutting," Proc. Inst. Mech. Engr., Vol. 177, No. 29, 1963, pp. 789-810.

49. Rapier, A. C., "A Theoretical Investigation of the Temperature Distribution in Orthogonal Cutting," Brit. J. Appl. Phys., Vol. 5, 1954, p. 400.

50. Boothroyd, G., Personal communications, 1964.

VITA

Cecil Reid Attaway was born in Fredericksberg, Virginia on May 19, 1940. He attended grammar school in Clinton, New Jersey and high school at Annandale, New Jersey. He entered Clemson University (then Clemson College) in 1958 and graduated with honors in June, 1962 in Mechanical Engineering. He received a commission as a Second Lieutenant in the United States Army Reserve in August, 1962.

In September, 1962 he enrolled in the Graduate Division of the Georgia Institute of Technology. In June, 1967 he was called to active duty by the United States Army and in June, 1968 was promoted to the rank of Captain. During his tour of duty he served as a Research and Development Coordinator for the Army Research Office, Durham, North Carolina. In 1968 he was awarded the degree of Master of Science by the Georgia Institute of Technology.